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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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COMPUTER TECHNIQUE FOR TRACING SEISMIC RAYS
IN TWO-DIMENSIONAL GEOLOGICAL MODELS
(Text)

By

Nazieh K. Yacoub, James H. Scott,
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June 4, 1968

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ABSTRACT

A computer program has been developed to study the effect of subsurface geology on the propagation of seismic rays. Based on ray theory, and on numerical solution of Zoeppritz' equations for any angle of incidence at elastic boundaries, the program traces seismic rays and energy distribution through geological models of any complexity, assuming that the geological units comprising the model are isotropic elastic homogeneous media with no attenuation to seismic energy, and that the model is two-dimensional with interfaces between rock units normal to plane of section.

Ray-path plots and amplitude calculation through two real two-dimensional geological models of Basin and Range geology, more than 100 miles long and as deep as to the Moho, show clearly the strong influence of spatial distribution and elastic properties of rock units on ray-path distribution. Amplitude calculation for rays arriving at ground surface through an actual geological section permits the prediction of ground motion based on geology rather than on empirical relations obtained from observed displacements regardless of geologic structure between the source and the recording station.

Comparison of calculated amplitudes and displacements at the earth's surface with observed displacements at a few recording stations along or near the models shows a reasonably good fit of data and suggests that seismic ray calculations, where sufficient subsurface data are available, would provide a valid means for ground motion prediction.

INTRODUCTION

Seismic measurements at stations in the vicinity of the U.S. Atomic Energy Commission's Nevada Test Site (NTS) have indicated that the intensity of ground motion resulting from underground nuclear explosions is not simply a function of the yield of the explosion, the depth of emplacement, or the distance to a seismic station.

The U.S. Geological Survey (USGS), has had a continuing project to study the effects of geology on ground motion that results from underground explosions at NTS. As a part of this study a computer technique has been developed for tracing seismic rays from an explosive source through a cross-sectional model of the earth's crust along some azimuth of interest. This report describes the computer technique in its present state of development and presents some preliminary results.

The authors are grateful to the computer staff of the Environmental Science Service Administration (ESSA) in Boulder, Colo. Special thanks to Jeanne M. Tucker of ESSA, for her criticism and advice concerning programming. Acknowledgment is also owed to W. H. Lee, J. D. Kibler, E. H. Wilson, R. J. Way, and Ingrid Hougland of Special Projects Branch (USGS), for digitizing the geological models.

GENERAL BACKGROUND

Most past studies of seismic wave propagation from underground explosions fall into two categories; the first category assumes a simple layered earth model in which the laws of reflection and refraction apply (Steinhard and Meyer, 1961). The second category assumes a model comprised of geologic units of arbitrary shape

represented by a two-dimensional array of elements of area, each element characterized by appropriate elastic constants, and each capable of transmitting forces to adjacent elements when deformed by external forces (Cherry and Hurdlow, 1966). Neither of the two approaches is well suited to our particular problem. The simple layered earth model of the first approach is not appropriate because of the structural complexity of rock formations in the Basin and Range province where nuclear explosions are tested. The second approach, while applicable in principal, is designed for detailed studies of the behavior of earth material near to the source point. Applying the second approach to cross sections 100 miles in length and 20 miles in depth (to the Mohorovicic discontinuity) would require oversimplification of the geological model, and even then, the computation would be inordinately expensive because of the large number of elements of area that comprise the model.

The computer technique developed by the USGS utilizes cross-sectional models comprised of rock units of any shape and size, and which are differentiated on the basis of their compressional-wave velocity, Poisson's ratio, and density. The units comprising the model are assumed to be perfectly elastic with no attenuation to propagating seismic rays. The models are assumed to be transparent to seismic waves except at interfaces joining units having different seismic properties, where Zoeppritz' equations for reflected and refracted compressional plane waves and vertically polarized transverse

plane waves are assumed to apply. Further, because the models are limited to two dimensions, the interfaces between different units are assumed to strike in a direction perpendicular to the plane of the cross section. Horizontally polarized transverse waves are disregarded because the model is a two-dimensional vertical cross section. The seismic energy source is assumed to be a point source, and the initial waveform is considered to be a unit pulse. Results obtained under these assumptions and considerations appear to explain some of the observed anomalies in ground motion intensity in the vicinity of NTS. The technique should be useful for making predictions of the relative intensity of ground motion at new sites where geology is known, but where no previous nuclear tests have been conducted.

AMPLITUDE, ENERGY, AND DISPLACEMENT EQUATIONS

Theoretical studies of seismic wave propagation in an isotropic elastic homogeneous medium indicate that waves travel in the form of an expanding sphere with the point source of energy at the center. In solid homogeneous media it is assumed that displacements and stresses are continuous throughout the media and across boundaries; and that Newton's third law is satisfied throughout. At a plane interface in a solid medium, assuming that displacements and stresses are continuous, one confronts the problem of matching the symmetry of a spherical wave with the plane interface. Brekhovskikh (1960, p. 238-242) handled the problem by using a transformation to expand the spherical wave into a plane wave. Using such a transformation eases the problem as the ray-wave theory is well established.

In the problem under consideration, two-dimensional ray theory is used for the following reasons:

1. Measurements made are far from the source where the spherical waves have very little curvature, and therefore, ray theory gives good approximations.

2. All the interfaces in the geological model can be approximated by straight line segments where they are intersected by rays.

3. Ray theory, because it is simpler, has been more completely developed than spherical wave theory.

One disadvantage of using ray theory is that it fails to deal with rays refracted at the critical angle and which travel along seismic interfaces. The errors that result from ignoring critically refracted ray energy are probably not too serious, however, because in the region of interest, which is far from the explosive source, most of the rays arriving at the surface are believed to arrive via paths that involve reflections and refractions at angles other than the critical angle.

Equations for partitioning the amplitude and the energy of an incident seismic ray at the interface between two elastic media were first developed by Knott (1899). Later Zoeppritz (1919) developed a similar set using a somewhat different approach. In both sets of equations the amplitude of an incident ray (either compressional- or transverse-wave) is usually partitioned into four possible emergent rays; (1) reflected compressional wave, (2) reflected transverse wave, (3) refracted compressional wave, and (4) refracted transverse wave.

Zoeppritz' and Knott's equations for incident compressional- and transverse-waves at the interface that separates two homogeneous isotropic media were programmed for the CDC-3800 computer. Zoeppritz' equations were reproduced from McCamy and others (1962), in which the source reference is given as Richter (1958). Knott's equations were reproduced from his original work (1899). In comparing the results of the two programs for the same set of input data, a discrepancy was noted in the sign of the reflected compressional waves that arose from an incident compressional wave. In order to determine the cause of the discrepancy the authors of this present report rederived the set of equations for incident compressional wave where the sign conflict was discovered. Results indicated that Zoeppritz' equations as stated by McCamy and others (1962) are in error, and that the equations given by Knott (1899) are correct. Our derivation is in agreement with those obtained by J. C. Hollister, Colorado School of Mines (oral commun., 1967).

In order to provide a means of computing amplitude partitioning of rays that arrive at a solid-air interface, the matrix in the two cases of each incident, P- and S-wave, are considered to be such that the transverse wave velocity equals zero. Notation used in presenting the two sets of equations and the two matrices is given in the following list.

<u>Type of Wave</u>	<u>Velocity</u>	<u>Amplitude</u>	<u>Angle normal to the plane at point of intersection</u>
Incident P	V_1	A	a
Incident S	v_1	B	b
Reflected P	V_1	C	c
Reflected S	v_1	D	d
Refracted P	V_2	E	e
Refracted S	v_2	F	f

P = abbreviation for compressional wave

S = abbreviation for transverse wave

The two sets of equations and the two matrices are represented as follows:

Set I: P-wave incident at the interface between two solid elastic media

$$A \sin a + C \sin c + D \cos d - E \sin e + F \cos f = 0$$

$$A \cos a - C \cos c + D \sin d - E \cos e - F \sin f = 0$$

$$A \cos 2d + C \cos 2d - D \frac{v_1}{V_1} \sin 2d - E \frac{\rho_2}{\rho_1} \frac{v_2}{V_1} \cos 2f - F \frac{\rho_2}{\rho_1} \frac{v_1}{V_1} \sin 2f = 0$$

$$A \sin 2a - C \sin 2c - D \frac{v_1}{V_1} \cos 2d - E \frac{\rho_2}{\rho_1} \left(\frac{v_2}{v_1} \right)^2 \frac{v_1}{V_1} \sin 2e + F \frac{\rho_2}{\rho_1} \left(\frac{v_2}{v_1} \right)^2 \frac{v_1}{V_2} \cos 2f = 0$$

Set II: S-wave incident at the interface between two solid elastic media

$$B \sin b + C \cos c + D \sin d - E \cos e - F \sin f = 0$$

$$B \cos b + C \sin c - D \cos d + E \sin e - F \cos f = 0$$

$$B \cos 2b - C \frac{v_1}{V_1} \sin 2c + D \cos 2d + E \frac{\rho_2}{\rho_1} \frac{v_2^2}{v_1 V_2} \sin 2e - F \frac{\rho_2}{\rho_1} \frac{v_2}{V_1} \cos 2f = 0$$

$$B \sin 2b - C \frac{v_1}{V_1} \cos 2c - D \sin 2d - E \frac{\rho_2}{\rho_1} \frac{v_2}{V_1} \cos 2f - F \frac{\rho_2}{\rho_1} \frac{v_2}{V_1} \sin 2f = 0$$

The matrix for the case of P-wave incident at a solid-air interface

A	C	D	E	F
$\sin a$	$\sin c$	$\cos d$	$-\sin e$	-1
$\cos a$	$-\cos c$	$\sin d$	$-\cos e$	0
$\cos 2d$	$\cos 2d$	$-\frac{v_1}{V_1} \sin 2d$	$-\frac{\rho_2}{\rho_1} \frac{V_2}{V_1}$	0
$\sin 2a$	$\sin 2c$	$-\frac{V_1}{v_1} \cos 2d$	0	0

The matrix for the case of S-wave incident at a solid-air interface

B	C	D	E	F
$\sin b$	$\cos c$	$\sin d$	$-\cos e$	0
$\cos b$	$\sin c$	$-\cos d$	$\sin e$	-1
$\cos 2b$	$-\frac{v_1}{V_1} \sin 2c$	$\cos 2d$	0	0
$\sin 2b$	$-\frac{V_1}{v_1} \cos 2c$	$-\sin 2d$	$-\frac{\rho_2}{\rho_1} \frac{V_2}{V_1}$	0

F, in the case of solid-air incidence, is equal to zero.

The energy content of any of the four emergent rays is given by

$$E = M^2 K \frac{\sin 2 \beta}{\sin 2 a} = M^2 K \frac{V_2}{V_1} \frac{\cos \beta}{\cos a}$$

where M is the ratio of the amplitude of the emerging ray, as computed from Zoeppritz' equations, to the amplitude of the incident ray, a is the angle of incidence and β is the angle of emergence, and K is the ratio of the density of the second medium to the first. The angles a and β are measured between the ray and the normal line crossing the interface at the point of ray incidence.

This equation reduces to

$$E = M^2$$

if the reflected ray is of the same kind (P or S) as the incident ray, or to

$$E = M^2 \frac{\sin 2 \beta}{\sin 2 a}$$

if the reflected ray is not of the same kind as the incident ray.

In terms of our notation the energy equations can be written as follows.

1. Case of incident compressional wave

$$C^2 + D^2 \frac{V_1}{V_1} \frac{\cos d}{\cos a} + E^2 K \frac{V_2}{V_1} \frac{\cos e}{\cos a} + F^2 K \frac{V_2}{V_1} \frac{\cos f}{\cos a} = E_p$$

Where E_p is the energy content of the incident compressional wave.

2. Case of incident transverse wave

$$C^2 \frac{V_1}{V_1} \frac{\cos c}{\cos b} + D^2 + E^2 K \frac{V_2}{V_1} \frac{\cos e}{\cos b} + F^2 K \frac{V_2}{V_1} \frac{\cos f}{\cos b} = E_s$$

Where E_s is the energy content of the incident transverse wave.

Phase angles can be computed from the real and imaginary parts of the complex amplitudes ($x + iy$) by the relation

$$\phi = \tan^{-1} \frac{y}{x}$$

The ground displacements at the earth's surface relative to the incident amplitude are as given by Gutenberg (1944 and 1952).

For incident compressional wave at the earth's surface

$$\begin{aligned} u/A &= - \frac{2V_1 v_1 \sin 2a \cot 2d}{V_1^2 \cot 2d \cos 2d + v_1^2 \sin 2a \cos 2d} \frac{\cos d}{\sin 2d} \\ &= - \frac{V_1}{v_1} \frac{8 \cot a \cot d \cot 2d}{(\cot^2 d - 1)^2 + 4 \cot a \cot d \cos 2d} \frac{\cos d}{\sin 2d} \\ w/A &= \frac{2V_1 v_1 \sin 2a \cot 2d}{V_1^2 \cot 2d \cos 2d + v_1^2 \sin 2a \sin 2d} \frac{\cos d}{\sin 2d} \\ &= \frac{V_1}{v_1} \frac{8 \cot a \cot d \cot 2d}{(\cot^2 d - 1)^2 + 4 \cot d \cot a \sin 2d} \frac{\cos d}{\sin 2d} \end{aligned}$$

For incident transverse wave at the earth's surface

$$\begin{aligned} u/B &= \frac{v_1}{V_1} \frac{2(\cot^2 b - 1)^2}{(\cot^2 b - 1)^2 + 4 \cot c \cot b} \frac{\sin c}{2 \sin^2 b} \tan 2b \\ w/B &= \frac{v_1}{V_1} \frac{2(\cot^2 b - 1)^2}{(\cot^2 b - 1)^2 + 4 \cot c \cot b} \frac{\cos c}{\cos 2b} \tan 2b \end{aligned}$$

u is the horizontal component of displacement.

w is the vertical component of displacement.

GENERAL DESCRIPTION OF COMPUTER PROGRAMS

From the functional point of view the computer programs used can be classified into two groups. The first group will be called the Computations Programs, the second group will be called the Plotter Programs.

Computation programs

This group of programs reads the two-dimensional digital representation of the geological model into the computer, traces the seismic rays through the model, solves Zoeppritz' equation wherever a seismic ray encounters geologic interfaces and stores on tape the following information for emerging rays intersecting the earth's surface: horizontal and vertical coordinates of point emergences, angle of incidence, ray type (P or S) amplitude, energy, phase angle, distance and time of travel from the shotpoint to the surface point, and the vertical and the horizontal components of relative ground motion at that point of emergence.

In some instances it is desirable to limit the tracing of seismic rays by stopping them at some preselected distance from the shotpoint. This may be desirable for two reasons: (1) the cost of computing results for a very large model is sometimes quite significant, and, consequently, it is desirable to detect any errors in design of the model close to the shotpoint which would cause erroneous results at great distances, or (2) it is of interest to determine the distribution and amount of energy traveling outward and downward relatively close

to the shotpoint so that the near-in effects of geology at different shotpoint locations in different media or at different depths in the same geological environment may be compared. Therefore a provision has been made in the computational programs for introducing a limiting circle of selectable radius beyond which rays are not traced. This option may be avoided by assigning a radius of zero to the limiting circle. If the circle option is chosen by assigning a radius greater than zero, ray paths are traced outward until either their energy falls below a preassigned cut-off value, or they intersect the circle. If they intersect the circle, the following information is stored on an output tape: angle between the shotpoint and point of intersection of the circle, angle of travel of the ray, type of ray (P or S), amplitude, energy, phase angle, and distance and time of travel from the shotpoint to the point of intersection. Data for rays intersecting the surface are also computed as described earlier, and are stored on another tape if the circle option is selected.

The operation of the computational group of programs, consisting of the main program SEISAVE and several subroutines, is discussed in detail in the following sections.

Program SEISAVE

The program was given this name because it uses a two-dimensional array, SAVE (I,J), where $I = 6,000$ and $J = 4$, for storing parameters of the seismic rays such as energy, amplitude, etc. The array makes

use of four storing areas as implied by the second dimension. The first of the areas ($J = 1$) is used to store the parameters for the reflected compressional waves. The second area ($J = 2$) is used for the reflected vertically polarized transverse waves. The third area ($J = 3$) is used to store the parameters for the transmitted compressional wave. The fourth area ($J = 4$) is used to store the parameters for the transmitted vertically polarized transverse waves. The program has three functions which divide it into three major parts.

Part I.--Input cards are read. These cards consist of four control cards and a large number of cards which contain the coordinates of points defining the boundaries of rock units that comprise the cross-section model.

The first of the four control cards contains the identification name of the problem.

The second contains the parameters YINCH and DELTA. YINCH specifies the width of the X-Y plot to be made. This parameter is used to compute the scale factors SFX and SFY, of the X-Y plotter coordinates, such that the horizontal scale is the same as the vertical scale for the plots. The parameter DELTA is used to establish the initial angle of the rays issuing from the shotpoint in a series of consecutive passes, each of which consists of a loop that increments the ray angles from an initial angle to a final angle using a specified incremental angle. For example, if the initial angle is zero and the

specified increment is 20° with clockwise incrementation up to a final angle of 360°, results will be computed for the angles, 0, 20, 40, 60, ...340, if DELTA is equal to zero, and this will be the first and only pass made. If DELTA equals 5, the program, after finishing the first pass, will increase the initial angle by 5 so that in the second pass, computations are made for angles, 5, 25, 45, 65, ...345, and then after completing the second pass, the initial angle is increased again to produce a third set for 10, 30, 50, 70, ...350, and the process will continue until the initial angle plus DELTA equals the incremental interval. The reason for choosing this logic is that the program can run for a very long time, and unless some protective technique is used the results of an entire run would be lost in the event of a machine failure during the run. The use of the logic described above permits recovering most of the data computed up to the time of a machine failure if one should occur.

The third card reads four parameters which are AX, BX, AY, and BY. These are used as constants in the following linear transformation equations:

$$X = x(BX) + AX$$

$$Y = y(BY) + AY$$

The transformation constants BX and BY make it possible to change the system of units of horizontal and/or vertical linear measurement (for example, inches to feet or feet to meters and/or visa versa).

The second constants AX and AY provide a means of translating the origin of the vertical and/or horizontal measurements to a different location if this should be desirable for any reason.

The fourth card contains the following parameters:

MSP = Identification number assigned to the medium where the shotpoint is located.

XSP and YSP = x- and y- coordinates of the shotpoint.

RSP = Radius of the limiting circle which has the shotpoint as center. Use of the limiting circle can be avoided, if desired, by setting $RSP = 0$.

A1 = Initial angle from the shotpoint in degrees.

AINC = Increments at which the rays from the shotpoint will be considered.

A2 = Maximum angle for rays from the shotpoint.

EPS = Ray energy cut-off value; all rays with energy less than EPS are discarded and ray paths are not followed beyond the point at which energy becomes less than EPS.

The rest of the input cards comprise two sets of cards which define the geological model.

The first set is concerned with the interfaces separating the different media and is divided into two n-subsets that correspond to n-interfaces, that is, each subset of cards represents an interface between two media having different elastic properties. The cards of each subset contain the following information:

ID = Identification number of interface.
 ISEQ = Sequence number of the card in the subset.
 M1(I) = Identification number of the first medium.
 M2(I) = Identification number of the second medium.
 II = Sequence number of that interface in the set.
 NJ = Total number of X- and Y-coordinate pairs which define
 the interface in the model.
 X(J), Y(J) = X- and Y-coordinates of points that define the
 interface.

Each card includes five pairs of X- and Y-coordinates, that is, five points on the interface. If the interface is defined by more than five points, which is usually the case, the points are continued on successive cards with ISEQ stepped up by 1 in each case, and the same M1, M2, II, NJ. The X- and Y-coordinates are stored in two arrays X(J), and Y(J) where $J = 2000$. The order of the end points of the interfaces are stored in another two arrays, JFIRST(I) and JLAST(I). The set is ended by a control card that contains the word ENDELV.

The second set contains the seismic parameters for the various media. Each medium is represented by one card that contains the following information:

J = Identification number of the medium.
 NJ = Total number of media (total number of cards in the set).
 PWV(J) = Compressional wave velocity of medium J.
 SIG(J) = Poisson's ratio of medium J.
 RHO(J) = Density of medium J.
 NAME(J) = Identification name of medium J.

The program computes the shear-wave velocity SWV(J) according to

$$SWV(J) = PWV(J) \sqrt{\frac{.5 - SIG(J)}{1 - SIG(J)}}$$

If any card in the two previous sets of cards is out of sequence an error message is given indicating which set and the sequence number of the card in question in the set, and the program is halted.

During reading of the X-Y coordinate points the program searches for, and stores for later use, the maximum and minimum values of the X-Y coordinates.

Part II.--The second part of SEISAVE computes the angles of the points of intersection of the limiting circle with the earth's surface. These angles are designated TFIRST and TLAST and are shown on figure 1.

Part III.--The third part of SEISAVE computes the parameters needed for tracing the seismic rays and for using the partitioning equations. These parameters are:

- X1 and Y1 = X-Y coordinates of the origin point of the ray.
- M = Medium in which the ray is travelling.
- AR = Angle of the ray from the vertical measured in a clockwise direction.
- AMI = Amplitude of the ray.
- TEN = Energy of the ray.
- PHAS = Phase angle of the ray.
- TI = Accumulative time required to reach point X1, Y1 along some particular segmented ray path from the shotpoint.
- DS = Accumulative distance to point X1, Y1.

Figure 1.- Illustration of program notation

After these parameters are computed the program calls for either one of two intermediate subroutines. If the ray is of the compressional type the intermediate subroutine LPPC will be called. If the ray is of the transverse type the intermediate subroutine LPSC will be called.

Subroutines LPPC and LPSC

The function of these two intermediate routines is primarily to manipulate other subroutines. Subroutine LPPC is used for tracing compressional waves while subroutine LPSC is used for tracing transverse waves.

Both subroutines compare the energy of the incident ray with the cutoff energy EPS. If the energy is less than or equal to EPS, control is returned to Program SEISAVE and another ray is considered. If the energy is greater than EPS subroutine LOCATE is called. Subroutine LOCATE searches the model for the intersection between the ray and the closest segment of the geological model. When the search is completed there are three possible outcomes:

1. No Intersection: In this case the ray goes out of model and no further computation for that particular ray is possible.

2. Circle Intersection: In this case the intermediate program (either LPPC or LPSC) writes the following parameters on tape unit 5.

IØ or IL, AN, TH, TH, AR, AMI, TEN, TI, PHAS, DS, ZERO, ZERO.

where

IØ or I1 = Code used to indicate the type of wave; IO for P-Wave,
I1 for S-Wave.

AN = Angle of the original ray issuing from the shotpoint.

TH, TH = Angle in radians, of a line drawn between the shotpoint
and the point of intersection of the ray with the circle
in the main reference frame. The reason for writing
TH on tape 5 twice is to make the tape format compatible
with the format of output 4 which is used for storing
information of rays arriving at the earth's surface.

AR = Angle of the path of the intersecting ray in the main reference
frame.

AMI = Amplitude of the intersecting ray.

TEN = Energy of the intersecting ray.

TI = Accumulative time from the shotpoint along the segmented ray
path to the point of intersection with the circle.

PHAS = Phase angle of the ray with respect to the phase angle of
the initial ray issuing from the shotpoint.

DS = Accumulative distance along the segmented ray path from the
shotpoint to the point of intersection with the circle.

ZERO, ZERO = Dummy parameter for format conformity, tapes 4 and 5.

3. Interface Intersection: In this case there are two possibilities:

- a. Rock-Air Interface: In this case the intermediate program LPPC or LPSC will call subroutine PW2 if the intermediate routine is LPPC or will call SW2 if the intermediate program is LPSC. PW2 and SW2 accomplish ray amplitude and energy partitioning for rock-air interfaces. The intermediate program will write the following parameters on tape 4.

$I\theta$, $I1$, AN, X2, Y2, AR, AMI, TEN, TL, PHAS, DS, U, W

The parameters are the same as those described earlier for the case of the circle intersection with the exception of the following:

X2, Y2 = X-Y coordinates of the intersection between the ray and the earth's surface.

U = Horizontal component of ground motion relative to amplitude AMI.

W = Vertical component of ground motion relative to amplitude AMI.

After these parameters are written on tape 4, the intermediate program LPPC or LPSC transfers to the Storage Section (described below) which stores information on rays reflected back into the model from the rock-air interface.

b. Rock-Rock Interface: In this case the ray intersects one of the interfaces between two elastically different media. The intermediate program LPPC or LPSC calls either subroutine PWAVE or SWAVE according to the type of ray. PWAVE and SWAVE accomplish ray amplitude and energy partitioning for rock-rock interfaces. After return from PWAVE or SWAVE, the intermediate program LPPC or LPSC transfers control to the storage section.

Storage Section: In the storage section, first subroutine CAMS is called to compute the angles of the emergent rays in the main reference frame. (In subroutines PW2, SW2, PWAVE, and SWAVE, emergent ray angles are computed with respect to the line normal to the model segment at the point of intersection.) Then parameters needed for continuing the tracing of emergent rays are stored in array SAVE as described below:

General parameters

SAVE (JW + 1, 1) = X2 (X-coordinate of the point of incidence).

SAVE (JW + 1, 2) = M (Identification number of the medium in which the incident ray and reflected rays travel).

SAVE (JW + 1, 3) = Y2 (Y-coordinate of the point of incidence).

SAVE (JW + 1, 4) = MM (Identification number of the medium in which the refracted rays travel).

T (JT + 1) = TI (Accumulative time).

DI (JT + 1) = DS (Accumulative distance).

For reflected P-wave

SAVE (JW + 2, 1) = ARP (Angle of reflection).

SAVE (JW + 3, 1) = AMRP (Amplitude).

SAVE (JW + 4, 1) = ENRP (Energy).

SAVE (JW + 5, 1) = PHRP (Phase angle).

For reflected S-wave

SAVE (JW + 2, 2) = ARS (Angle of reflection).

SAVE (JW + 3, 2) = AMRS (Amplitude).

SAVE (JW + 4, 2) = ENRS (Energy).

SAVE (JW + 5, 2) = PHRS (Phase angle).

For transmitted P-wave

SAVE (JW + 2, 3) = ATP (Angle of transmission).

SAVE (JW + 3, 3) = AMTP (Amplitude).

SAVE (JW + 4, 3) = ENTP (Energy).

SAVE (JW + 5, 3) = PHTP (Phase angle).

For transmitted S-wave

SAVE (JW + 2, 4) = ATS (Angle of transmission).

SAVE (JW + 3, 4) = AMTS (Amplitude).

SAVE (JW + 4, 4) = ENTP (Energy).

SAVE (JW + 5, 4) = PHTP (Phase angle).

The first index of the variables will be stepped as follows for the next ray.

JT = JT + 1 and JW = JW + 5.

Subroutine LOCATE

Given $X1$ and $Y1$ (the coordinates of the source point of the ray segment under consideration) M (the identification number of the medium in which the ray is travelling) and AR (the angle of the ray in the main reference frame) subroutine LOCATE finds the type of intersection and sets the flag parameter KEY accordingly. When operation of LOCATE is completed, one and only one of the following cases is established.

Case 1. Interface Intersection: $Key = 1$. The subroutine determines the closest point of intersection of the ray (travelling in medium M) with a segment of the model separating medium M from some other medium. The coordinates of the point of intersection ($X2$, $Y2$) are determined along with the identification number of the medium, MM , on the other side of interface. Knowing M and MM the program will determine the appropriate medium properties for media on both sides of the interface (compressional and transverse velocities, the Poisson's ratio and the densities). The program also computes the angle of incidence between the ray and the normal line at the point of intersection on the model segment.

Case 2. Circle Intersection: $Key = 0$. If the radius, RSP , of the limiting circle is not equal to zero the program will search for a possible circle-ray intersection. If one is found, and if it is closer to the source point of the ray than the intersection determined in Case 1 (above), the parameter KEY will be changed from 1 to 0. In order to test for the closest intersection in cases 1 and 2, the program computes the distance travelled from the point ($X1$, $Y1$), the origin of the ray segment to the candidate points of closest intersection ($X2$, $Y2$).

Case 3. No Intersection: Key = -1. If no intersection is found between the ray segment and any of the model segments or with the circle, the conclusion to be drawn is that the ray goes out of model. This case cannot exist if a limiting circle is used in the computation ($RSP \neq 0$), because all rays not intersecting surface or subsurface model segments must intersect the circle. When no limiting circle is used ($RSP = 0$), rays may escape from the side or lower boundaries of the model without intersecting any model segments.

Subroutines PWAVE, SWAVE, PW2 and SW2:

Four routines are used to solve Zoeppritz' equations for the four different sets of equations on pages 8 and 9. The function of each subroutine is as follows:

Subroutine PWAVE solves Zoeppritz' equations for the case of an incident compressional wave at a rock-rock interface.

Subroutine SWAVE solves Zoeppritz' equations for the case of an incident transverse wave at a rock-rock interface.

Subroutine PW2 solves Zoeppritz' equation for the case of an incident compressional wave at a rock-air interface.

Subroutine SW2 solves Zoeppritz' equation for the case of an incident transverse wave at a rock-air interface.

Given the compressional and transverse wave velocities and the densities of the two media, together with the angle of incidence of the ray, the solution of any of the four sets of equations boils down to a numerical solution of a 4×4 matrix.

The emerging angles are computed according to Snell's law

$$\frac{\sin a}{v_1} = \frac{\sin d}{v_1} = \frac{\sin e}{v_2} = \frac{\sin f}{v_2}$$

In some instances the computed sine of one or more of the angles of emergence is greater than one, indicating that the angle is greater than or equal to the critical angle, in which case the angle of emergence is considered to be imaginary. If one or more of the emerging angles are found to be imaginary, Zoeppritz' equations must be solved by use of a complex rather than a real matrix.

In evaluating the matrices, either the imaginary or the real case may be encountered, except when a P-wave is incident on a rock-air interface. Consequently subroutines PWAVE, SWAVE, and SW2 are all designed to handle either real or imaginary cases.

Case of Real Matrix: All emerging rays possess angles less than their corresponding critical angles, that is, the sines of all emerging angles are less than 1 and consequently the cosine functions do not have a negative argument under the square root sign.

$$\cos \alpha = \sqrt{1 - \sin^2 \alpha}$$

To solve the matrix, subroutine RMSIM is called first. This subroutine is based on a method by P. D. Crout (1941). Crout's method, though very efficient, fails in case one element of the auxiliary matrix approaches zero or the first element is zero. A test is made to determine whether this situation exists, and if it does, another

routine, MATPAC is called, which uses Gauss-Seidel method. Although MATPAC is slower than RMSIM by 6 milliseconds, it gives a meaningful result in most cases where RMSIM does not. If the determinant of the matrix is less than 10^{-300} a message is given that the matrix is singular and no solution is given.

Case of complex matrix: If one or more of the emerging angles is imaginary, causing the sine of the angle to be greater than one, the cosine function will be

$$\cos \alpha = \pm i \sqrt{\sin^2 \alpha - 1}$$

The sign convention of the cosine function is taken as negative for transmitted rays and positive for reflected rays in order to fulfill the requirement that the potential function must be bounded (Jeffreys, 1952, p. 30). The possible imaginary angles are shown in figures 2, 3, and 4. Note that in the case of incident compressional wave at a rock-air boundary there are no imaginary angles and that is why only the real case need be considered for subroutine PW2. For solving complex matrices, two subroutines CMSIM and CMATPAC are available. These are used in the same way as RMSIM and MATPAC, with CMSIM used in preference to CMATPAC, because it is faster, and with CMATPAC used when a solution cannot be obtained with CMSIM because of the reasons mentioned previously for RMSIM.

The matrix solving subroutines provide the amplitude of the emerging rays relative to the amplitude of the incident ray. After the relative amplitudes of the emerging rays are determined, the

Possible imaginary angles are:

1. e for $e > \sin^{-1}(\frac{V_2}{V_1} \sin a)$
2. f for $f > \sin^{-1}(\frac{V_2}{V_1} \sin a)$

Possible imaginary angles:

None

Figure 2-Incident P-Wave

Possible imaginary angles are:

1. c for $c > \sin^{-1}(\frac{V_1}{V_2} \sin b)$
2. e for $e > \sin^{-1}(\frac{V_2}{V_1} \sin b)$
3. f for $f > \sin^{-1}(\frac{V_2}{V_1} \sin b)$

Possible imaginary angles are:

1. c for $c > \sin^{-1}(\frac{V_1}{V_2} \sin b)$
2. e for $e > \sin^{-1}(\frac{V_2}{V_1} \sin b)$

Figure 3-Incident S-Wave

Possible imaginary angles
None

Possible imaginary angles
c for $c > \sin^{-1} \left(\frac{V_1}{V_2} \sin b \right)$

Figure 4.-- Incident P- and S- Waves at the earth's surface

energy of each ray is computed along with the phase angle in the complex cases. The output of subroutines PWAVE, SWAVE, PW2, and SW2 provides four sets of data, one for each of the four emerging rays. Each set is comprised of four elements:

1. Angle between the emerging ray and the normal to the interface.
2. Amplitude.
3. Energy.
4. Phase angle (zero except in complex cases).

The first set contains elements pertaining to the reflected compressional wave. The second set contains elements pertaining to the reflected vertically polarized transverse wave. The third set contains elements pertaining to the transmitted compressional wave. The fourth set contains elements pertaining to the transmitted vertically polarized transverse wave. In addition to these four sets, subroutines PW2 and SW2 give another set that contains the vertical and horizontal components of ground motion relative to the amplitude of the incident ray. Also, in these two subroutines the elements of the fourth set is set to zero since there is no transmission of shear waves into the air. All four elements are set to zero in the case of an imaginary ray.

Plotter programs

This group of programs consists of two main programs with related subroutines that plot information of interest on (1) a standard high-speed printer or on (2) an X-Y plotter. The printer-plotter program is called SORTPLOT, and is used to obtain preliminary inexpensive

approximate plots and to generate tapes containing data sorted for more efficient handling by the X-Y plotter program which are called EADCAL and EADGER. The difference is that (EADCAL) uses a Calcomp plotter while (EADGER) uses Gerber plotter. The function of the two programs is to plot energy or amplitude or ground motion versus distance, for the rays arriving at the earth's surface. For plotting the geological model another two programs are used which are CALPLOT and GERPLOT (for the Calcomp and Gerber plotters, respectively). The reason for having two plotter programs for the same purpose is the difficulty in finding a satisfactory plotter. A second version of the program SEISAVE has been developed which performs all of the previously described functions of SEISAVE, and in addition, prepares a tape for plotting all rays traced by the program on the Gerber plotter. This version is called SMORYPLT.

Program SORTPLOT

Input data to this program are presented in three possible forms:

- (1) One output tape from program SEISAVE containing data for rays intersecting the earth's surface of the model for the case when no limiting circle is used ($RSP = 0$).
- (2) Two output tapes from program SEISAVE, one containing data for rays intersecting the surface of the model, and the other containing data for rays intersecting the circle for the case where the limiting circle is used ($RSP > 0$).

(3) One output tape from a previous run of program SORTPLOT containing surface, or surface and circle ray data sorted so that surface ray data occur sequentially in order of increasing X (the horizontal axis of the model) and so that circle ray data occur sequentially in a counterclockwise direction from the left circle-surface intersection to the right circle-surface intersection.

If form (3) of input data presentation is used, the sorting section of the program is bypassed and the plotting section is entered directly. Plots are made by summing ray amplitude, energy, or relative ground-motion values for all rays arriving in successive increments of horizontal distance in the case of rays intersecting the surface, or in successive increments of angle in the case of rays intersecting the limiting circle, and in successive increments of time for those plots where time is represented by one of the axes. These distance, angle, and time increments can be assigned any value desired by use of a control card. Therefore form (3) of input data presentation may be used repeatedly with sorted data plotted for various values for the increments.

Sorting of input data in form (1) or (2) is accomplished in program SORTPLOT by a series of sort and merge operations. Sorting is done in blocks of data having a size such that most of the high-speed internal storage of the machine is occupied. After the sorting of a block of data is completed, the sorted data are placed on tape or drum, and another block is brought into high-speed storage for sorting. After this operation is completed the sorted data in

high-speed storage is merged with sorted data stored on tape or drum, the merged data are stored back on tape or drum. This process is continued until all input data are sorted. In the case of input form (3) where both surface and circle ray data are presented for sorting, the sorted results for both types of data are written on separate sections of a single output tape with sorted surface ray data in the first section and sorted circle ray data on the second. When the final merge is accomplished, all sorted data are written on an output tape which is saved for future use, and can be read back into machine memory if plotting is desired immediately after sorting. At the user's option, a listing of all sorted data may be made immediately after the output tape of sorted data is prepared.

After sorting is complete, but prior to actual plotting, summations are made over the preselected increments of distance, angle, and time as described previously. As the summations are made the maximum and minimum values of energy, amplitude, and ground motion (in the case of surface rays) are sought and stored for later use in determining automatically the scales and labeling of scales to be used in the individual plots. A printer listing is made of all maximum and minimum values and a key is printed to the symbols used in some of the plots to represent order-of-magnitude, ranges of amplitude, energy, and ground motion.

Printer plots are of two main types: (1) time-distance or time-angle plots where values of amplitude or energy are summed over preselected increments of distance or angle and time, and are represented on the plot by numbers which represent order-of-magnitude ranges, and (2) parameter-distance or parameter-angle plots where the parameters amplitude, energy, or ground motion are summed over preselected distance or angle increments from the time of the shot moment to the time of the latest arriving ray, and the format of the plot is that of a bar graph where the length of the bars represent the magnitude of the parameters.

The first type of plot is made by use of a subroutine called TDPLOT, and the second by a subroutine called BARPLOT. Individual plots of the following types may be selected by appropriate designation on a control card read by program SORTPLOT. Any number of plots from 0 to 10 may be selected.

Case of surface-ray plots:

1. TDPLOT with energy symbolized by printed numbers.
2. BARPLOT with energy represented by length of bars.
3. TDPLOT with amplitude symbolized by printed numbers.
4. BARPLOT with amplitude represented by length of bars.
5. BARPLOT with vertical component of ground motion
represented by length of bars.
6. BARPLOT with horizontal component of ground motion
represented by length of bars.

Case of circle-ray plots:

1. TDPLOT with energy symbolized by printed numbers.
2. BARPLOT with energy represented by length of bars.
3. TDPLOT with amplitude symbolized by printed numbers.
4. BARPLOT with amplitude represented by length of bars.

Subroutine TDPLOT

After an appropriate heading is printed on the top of the page by program SORTPLOT, the subroutine is called. First TDPLOT computes and prints the appropriate time scale across the page under the heading. Then, starting at the left-hand side of the model (or circle), a series of lines of type are printed with the final (bottom) line representing the right-hand side of the model (or circle). Each line of type represents a preselected distance (or angular) increment. Each column of type represents a preselected increment of time, with the leftmost column representing the increment starting at the shot moment. If the selected time scale is such that the time of arrival of the latest arriving ray falls to the right of the rightmost column on the sheet, successive continuation sheets are plotted until the latest arriving ray can be represented. Type symbols are preselected automatically in program SORTPLOT to represent order-of-magnitude ranges of the parameter to be presented on the plot (amplitude or energy). The appropriate symbol is determined by the magnitude of the parameter summed in the time-distance or time-angle element represented by each printer symbol position. Parameter summing is accomplished within the subroutine by successively reading segments of the sorted data tape

into main storage. Upon completion of an individual plot the sorted data tape is rewound by use of subroutine SKIPBACK to the starting point of surface (or circle) ray data in preparation for the next plot. If all sorted data can be read into main memory at one time, no tape manipulation (reading and rewinding) is required. After completion of an individual plot, control is returned to the main program SORTPLOT where selection of the next plot is made.

Subroutine BARPLOT

After an appropriate heading is printed on the top of the page by program SORTPLOT, the subroutine prints a logarithmic scale for the parameter to be represented along the horizontal axis (amplitude, energy, or ground motion). The scale is determined automatically by program SORTPLOT. Then, starting at the left-hand side of the model (or circle), a series of lines of type are printed with the final (bottom) line representing the right-hand side of the model (or circle). Each line of type represents a preselected distance (or angular) increment. Bars composed of strings of X's are printed from left to right such that the length (number of X's) represents the magnitude of the logarithm of the parameter being displayed. Summations of the parameter are made over all time from the shot moment to the time of the latest arriving ray in the distance (or angular) element represented by each line. The summations are accomplished within the subroutine by successively reading segments of the sorted data tape into main memory. Upon completion of an individual plot the sorted

data tape is rewound by use of a subroutine SKIPBACK to the starting point of surface (or circle) ray data in preparation for the next plot.

If all sorted data can be read into main memory at one time, no tape manipulation (reading and rewinding) is required. After completion of an individual plot, control is returned to the main program SORTPLOT where selection of the next plot is made.

The general logical flow of program SORTPLOT and subroutines TDPLLOT, BARPLOT, and SKIPBACK is shown on the flow chart of figure 5.

X-Y plotter programs

An X-Y plotter, Gerber Scales 600, model 622, was used to make all plots shown in this report. The plots were made by using scribe pens and scribecoat drafting material. The Gerber 622 uses an M-12 buffered magnetic tape converter. The tapes are prepared by the CDC-3800 computer through the following programs:

Program GERPLOT:

This program prepares a tape to plot the geological model for checking the digitizing of the subsurface structure.

Program SMORYPLT:

This program is a modification of program SEISAVE which performs all of the functions of SEISAVE, and in addition plots the geological model and the seismic rays traced in the model.

Figure 5.--Generalized flowchart for: Program SORTPLOT, Subroutine BARPLOT, Subroutine TDPLOT, Subroutine SKIPBACK

Program EADGER:

This program plots energy, amplitude, and displacement (vertical and horizontal) against distance for rays arriving at the earth's surface. It uses the sorted tape prepared by program SORTPLOT. The program enables the user to plot the data on a linear-linear scale or linear-log scale through the following two subroutines:

(a) Subroutine ORGPLOT: This subroutine gives linear-linear plots. It divides the area for plotting in two areas such that the Y-scale factor is the same. The upper area is for positive values of the Y-parameter and the lower area is for the negative values of the Y-parameter. This is used for amplitude and displacement plots only.

(b) Subroutine LOGPLT: This subroutine gives linear-log plots. The reason for having a linear-log plot is that Y-parameter commonly has a very wide range, 10^0 to 10^{-13} and 10^0 to -10^{-13} , such a wide range in values can not be displayed on a linear-linear plot. To overcome the problem of taking the logarithm of negative numbers, the plotting area is divided as in the case of subroutine ORGPLOT in two parts. The negative values of the Y-parameter are considered as positive and plotted in the area below the X-axis while the positive values of the Y-parameter are plotted in the area above the X-axis.

SELECTION OF GEOLOGICAL MODELS

Prior to the development of the computer program, geologic cross sections had been constructed as part of an effort to help evaluate the seismic information obtained under programs conducted by the Environmental Research Corporation and the U.S. Coast & Geodetic Survey for the Atomic Energy Commission. Two of these geologic cross sections were selected as models for the computer program (fig. 6). Though control for constructing cross sections from the Nevada Test Site is better along some directions other than the directions to the Toiyabe Range and Las Vegas, these two sections were selected to test the application of the computer technique because of (1) a large contrast in the geology shown by the cross sections, (2) more seismic data are available than along other cross sections, and (3) relatively large differences in some seismic signals have been observed along the Toiyabe and Las Vegas sections.

The model cast from one of these cross sections (fig. 7a) extends N. 32° W. for 110 miles from the deepest (13,686 feet) drill hole, UE20f, in Nevada on Pahute Mesa, Nevada Test Site. This section herein referred to as the "Toiyabe model" was constructed by R. E. Anderson (1967). The other cross section used as the basis for a model (fig. 8a) extends from drill hole UE20f S. 43° E. for 143 miles through Las Vegas to Nelson, Nev. The part of this section that extends from UE20f to approximately seismic station SE-2 was constructed by Hedlund (1966); the remainder of it, from SE-2 to Nelson, was constructed by W. D. Quinlivan (1966, written commun.). The line along which the model was drawn has a small bend

Figure 6.- Index map showing lines of geologic models

near station SE-6. The accuracy of the calculations of rays and displacement amplitudes between SE-6 and Nelson is probably not seriously affected by this bend. For convenience, this section will herein be referred to as the "Las Vegas model". Both models were compiled from many sources of published and unpublished data as well as some original field work by Anderson, Hedlund, and Quiplivan.

In order to use the geologic sections as models in the computer program the geologic units had to be recast into rock units of different elastic properties whose boundaries were then digitized. The differences in the elastic properties between these rock units is the sole result of differences in lithologic characteristics rather than any arbitrarily established numerical difference. Recasting involved combining lithologic units with similar physical properties, generalizing shapes of units, and omitting some very small units. The small units were simply merged with a contiguous larger unit.

Digitizing required defining all interfaces in the models by coordinates. In order to avoid determining and using an extremely large number of coordinates the detailed configuration of some interfaces was slightly modified to make them parts of straight lines or smooth curves. The digitization was checked by having the model plotted on either a Calcomp or Gerber plotter (figs. 7a and 8a). The elastic values shown in the explanation of the figures are selected averages from sample and geophysical log measurements cited in Anderson (1967, tables 1, 2, and 3), Hedlund (1966, table 1), and Press (1966, tables 9-2, 9-4). Variation of the velocity and density with depth of burial of the units is estimated

as described in following parts of the report. The interfaces between different rock units with different elastic properties will be hereafter referred to as elastic discontinuities.

The depth of the models was limited to the Mohorovicic (M) discontinuity, principally because perturbations in a seismic signal from a source within about 100 miles are generally attributed to geologic characteristics within the crust.

It cannot be overemphasized that the construction of both the original geologic cross sections and the models required considerable subjective interpretation of the distribution and characteristics of rock units at great depths. Though detailed explanation of the evolution of the models shown in figures 7a and 8a is not warranted in this report, some of their principal features and the guidelines used to recast the geology are appropriate. The reader is referred to Anderson (1967) and Hedlund (1966) for the geology from which the models are cast.

Toiyabe model

The geology along the Toiyabe section (fig. 7a) is particularly difficult to infer at great depths because of relatively poor outcrop control and abundance of complex relations of igneous rocks. The distribution and properties of igneous rocks at depth are highly speculative.

Drill hole UE20f, in which the source of seismic signals is assumed in the models, is at the southeast end of the section. The hole is within the Silent Canyon caldera, which contains very thick units of rhyolite,

welded and nonwelded tuff. Between the caldera and the Cactus Range volcanic units are inferred to thin over a buried granodiorite stock penetrated in drill hole PM#2 and over Precambrian crystalline rocks exposed in the Trappman Hills. Volcanic rocks of intermediate composition, the granodiorite, and the crystalline rocks are all assumed to have a velocity of 18,000 fps and density of 2.65 g/cc to a depth of 16,000 feet. Above this depth, which corresponds approximately with an overburden pressure of 1,000 bars, most rocks are not likely to have their ultimate velocity and density in situ; fracture porosity is probably highly effective in controlling the gross physical properties of large masses of rock at shallow depths. Below a depth of 16,000 feet all except carbonate and highly mafic rock types are assumed to have a velocity of 21,000 fps and a density of 2.7 g/cc. Though the elastic discontinuity inferred at 16,000 feet is probably gradational, velocity-pressure curves (Press, 1966, fig. 9-7) indicate that at pressures less than 1,000 bars velocity is highly dependent upon pressure, but at pressures greater than 1,000 bars increased pressure has relatively little effect on velocity. This discontinuity at 16,000 feet will herein be referred to as the 1,000-bar discontinuity.

Below the welded tuffs that crop out extensively in the Cactus Range, complexly faulted intrusive rocks of intermediate composition are inferred by Anderson (1967, fig. 1) and are combined into one elastic unit in the model because of the probability that they have similar compositions.

Outcrops of volcanic rocks along the edges of Ralston Valley indicate that it is a structural basin. The exposed and inferred thicknesses of the volcanic rocks are projected beneath the valley in a simple basinlike form. Undoubtedly, however, the rocks beneath the valley are highly faulted.

The San Antonio Mountains, according to Anderson (1967, p. 26), is "a north-trending east-tilted basin and range structural block bounded and broken by numerous north-trending normal faults". Both the structural characteristics and inferred intrusive rocks at depth make the San Antonio Mountains similar geologically to the Cactus Range. This similarity is apparent in the model.

A pronounced change in geology occurs under Big Smoky Valley and the south end of the Toiyabe Range. The south end of a major depositional basin underlies these areas. Relatively thick units of clastic and carbonate sedimentary rocks fill the basin and have elastic properties that contrast moderately with the contiguous igneous and Precambrian crystalline rocks. Most of the rocks in the basin are either carbonate or volcanic-clastic rocks with densities probably ranging from 2.7 to 2.8 g/cc. The carbonates are assumed on the basis of sampling to have a velocity of 20,000 fps; the volcanic-clastic rocks are assumed to have a velocity of 18,000 fps on the basis of two samples. The depths to the Conrad and Mohorovicic (M) discontinuities were obtained from published and unpublished data of the U.S. Geological Survey Crustal Studies Branch (Anderson, 1967, pp. 33-34).

Las Vegas model

The Las Vegas model is more complex than the Toiyabe model. Geologic information from which the model is cast is much better than that available for the Toiyabe model; therefore, validity is greater even though the geology appears more complex. In general, the Las Vegas model shows a volcanic center at the northwest end bounded by a very thick zone of sedimentary rocks that thins southeastward to form a wedgelike composite unit within the upper crust. The interface of the lower with the upper crust rises slightly southeastward except for a relatively sharp rise in the middle of the model. The edge of another volcanic area is shown at the southeast end of the model.

The thick zone of volcanic rocks at the northwest end of the model is part of the Silent Canyon and Timber Mountain calderas. Buried silicic intrusive rocks can reasonably be inferred to lie below the calderas down to depths great enough for the velocity and density of the rock to be maxima. The volcanic rock that fills the calderas has a wide range of velocities and densities and the distribution of units is much more complex than shown in the model. The wedgelike composite unit of sedimentary rocks southeast of the calderas is made up of thick layers of carbonate rocks, quartzose clastic rocks, and argillaceous clastic rocks with a known aggregate thickness of about 40,000 feet. Unless thrust faulting in the subsurface is totally unlike that shown in the Las Vegas section by Hedlund (1966, fig. 1), the thicknesses of the various rock types shown in the model are reasonably correct. The units shown in the model are the result of combining lithologic units

of similar velocities and densities. The 1,000-bar elastic discontinuity that is inferred in the Toiyabe model is not inferred in the Las Vegas model except at the southeastern end, where discontinuities in silicic intrusive and in volcanic rocks are inferred to lie at depths of 16,000 and 20,000 feet, respectively. The Las Vegas model contains a very large percentage of carbonate and clastic rocks, part of which occur below a depth of 16,000 feet. Unlike volcanic rocks which have a fabric and mineralogy that permits moderate changes in porosity with increased confining pressure, carbonate rocks and clastic monomineralic rocks like dolomite and quartzite have very little porosity and, therefore, have high velocities and densities at shallow depths. The 1,000-bar elastic discontinuity, therefore, is not reasonable for most of the Las Vegas model.

DESCRIPTION AND EVALUATION OF RAY AND AMPLITUDE PLOTS

In order to evaluate the practical application of the computer techniques described in the previous sections of this report, the ray paths and amplitudes of vertical displacements calculated from the geologic models must be compared with seismic measurements. The available data cannot be used, however, to make a rigorous test of the computer programs. Only a few seismic stations from which data are available were located exactly on the lines of the selected geologic cross sections. Furthermore, the explosions, which were the source of the seismic signals, were located several miles from each other. The ideal test would require many seismic measurements from stations along a line below which the

geology is well known, and a single source of seismic signals. Such requirements cannot be met at this time.

In addition to the lack of precise seismic and geologic information, the computer ray paths and displacement amplitudes are based on a relatively few number of rays from the source of seismic energy.

More complete discussion of factors precluding a mathematically rigorous correlation between calculated and measured values of ground motion is given below. Nevertheless, synthesis of relatively imprecise data shows clearly the effect of geology on the path of seismic rays and suggests a reasonably good correlation between calculated and measured amplitudes of vertical displacement.

The calculated ray paths and amplitudes of displacement for the two geologic models are plotted in figures 7b, 7c, 7d, 8b, 8c, 9a, 9b, 9c, and 9d.

Figures 7b, 7d, and 8b show ray path plots made with the SMORYPLT program. The origin of the rays shown in these figures is at a depth of 3,500 feet (2,500 feet above sea level) in drill hole UE20f. From this point source rays were assumed to radiate in the same plane as the cross section. A total of 10 rays was assumed at the source for the plots in figures 7b and 8b; the first ray was directed vertically upward, 0° from the vertical. The remaining rays were directed sequentially at angular increments of 20° , the last ray being directed 180° from the vertical. These initial rays cannot be identified in the ray path plots because of the many reflected and refracted rays generated at each interface in the model. Figure 8b, shows rays calculated to a 10^{-3} energy

cutoff for the Las Vegas model; figure 7b shows rays calculated to a 10^{-4} energy cutoff for the Toiyabe model. The plots show the distribution of all reflected and all refracted rays generated by the original 10 rays from the point source. Figure 7d is a ray plot of rays emerging from the source at 1° angular increments and calculated to an energy cutoff of 10^{-2} .

Detailed examination of figures 7b, 7d, and 8b shows that many rays terminate at an interface of units and some rays terminate within a unit. Termination of a ray at an interface is due to the limitation imposed by the choice of the energy cutoff level. Termination within a unit is due to improper scribing. Another error in plotting is the improper placement of the point of intersection of rays and interfaces due to the accumulative round-off of the coordinate points.

The amplitude of vertical displacements of rays terminating at the earth's surface is represented by short lines (figs. 7c, 8c, and 9a-d). The midpoint of a line is the value of the displacement calculated by the program.

Toiyabe model ray plot

Figures 7b and 7d are particularly useful illustrations, because of the large number of rays in them, of the affect of geology on the path of seismic rays. Zones of high and low density of rays are obvious; furthermore, all major and many minor geologic controls of the paths of seismic rays are apparent.

The first major control of seismic rays nearest the source is the wedgelike sequence of volcanic and silicic plutonic and hypabyssal rocks that are found from the edge of Silent Canyon caldera to the vicinity of Trappman Hills. The distribution of this moderately low velocity unit, Tw 2, is such that many rays are trapped in it and the distribution of rays emerging from the vicinity of Pahute Mesa are grossly changed (fig. 7d). One result of the redistribution is that an apparent source of rays, where the density of rays is particularly high, occurs in a zone 10,000-40,000 feet from the real source.

Both the Conrad and M discontinuities are major controls of the distribution of rays beyond about 180,000 feet from the source. Reflection of rays off these discontinuities occurs at angles that result in a relative shadow zone where ray density is low between distances of 120,000-250,000 feet and relatively high from about 330,000 feet to the northwest end (570,000 feet) of the model.

The 1,000-bar discontinuity acts as a major control in two ways (1) because the rocks above the discontinuity have a lower velocity than rocks below it a large number of rays are trapped above the discontinuity, and (2) it acts as a principal reflector of rays reflected from the Conrad and M discontinuities. Though these controls are easily recognized in figure 7b, their effect is not obvious because of the greater apparent affect of small-sized units above the 1,000-bar discontinuity.

Near-surface units above the 1,000-bar discontinuity exercise large control of the distribution of rays locally. One of the most obvious examples of such control is in the subsurface of Ralston Valley. Here

a relatively low velocity unit, Tb-3, which is concave upward and overlain by a high velocity unit Ug-5, acts as a concave reflecting mirror of rays from below. Most of the relatively few rays that emerge upward from Tb-3 become trapped in the thin alluvium Qa-1 at the surface of Ralston Valley. Partly because of the effect of Tb-3 and partly because of reflections off and refractions at the Conrad discontinuity, a very high density of rays occurs near and at the surface between distances of 330,000 and 360,000 feet from the source. As Tonopah, Nev. (figs. 1 and 7a) is in the same relative position with respect to Ralston Valley and only 5 miles southwest of the Toiyabe geologic model, the high seismic response recorded at Tonopah for events at Nevada Test Site may be explained by the ray path plot. Furthermore, though the subsurface geology of Ralston Valley is actually unknown, the number of rays reaching the surface in the vicinity of Booker Mountain and Tonopah might be considered important if the basin underlying the valley were not there. As pointed out above the shadow zone between distances of 120,000-330,000 feet from the source is the result of the angle at which rays are incident to and reflected off the M and Conrad discontinuities. Therefore, the number of rays reaching the surface in the vicinity of Booker Mountain would be higher than in the Ralston Valley-Cactus Range area even without the presence of the basin. The basin shown in the model seems to change local concentrations of rays but not the gross distribution of rays throughout the model.

Local units of Tw-2 juxtaposed with a higher velocity unit Ug 5 in the San Antonio Mountains also results in zones of high seismic ray density. Here too, the number of rays reaching this area is grossly controlled by reflection off the M and Conrad discontinuities.

The most spectacular zone of high seismic ray density, however, is in the alluvium of Big Smoky Valley. This high density is the result of a large number of rays reaching the base of the alluvium by reflections and refractions at the M, Conrad, and 1,000-bar discontinuities and being trapped in the thick alluvium, Qa-1, of the valley.

Las Vegas model ray plot

Explanations and interpretations of the variations in the density of seismic rays shown in figure 8b would be very dubious without the displacement amplitude plots (figs. 8c, 9a, 9b, 9c, and 9d) that follow and the very detailed ray plot of the Toiyabe model. The 10^{-3} energy-cutoff level used for the Las Vegas model ray plot does not provide enough rays throughout the model to assure that a representative sample of the distribution of rays is obtained. Comparison of figure 8b, however, with the amplitude plots which are calculated to a 10^{-4} energy-cutoff level and at smaller angular increments, shows that even the much fewer number of rays reaching the surface in or near the surface in figure 8b is a reasonably good sample of the distribution of rays.

As in the ray plot of the Toiyabe model, the first significant geologic control of the distribution of rays in the Las Vegas model is within about 100,000 feet of the source. Here relatively low velocity

units like Tv-1, Tw-2, Tr-4, and Tb-3 in the moat of Timber Mountain caldera exercise control of a large number of rays. Unlike the Toiyabe model, however, the density of rays is greatest around the source point. Also an apparently larger percentage of rays reach the Conrad and M discontinuities at higher angles below the source in the Las Vegas model as compared with the Toiyabe model. Most of these high-angle rays are not reflected off the M discontinuity and are lost out of the model.

The next most significant feature shown in figure 8b and 8c is the relatively few rays that reach the surface in the Las Vegas Valley area. Even figure 8c, which is a composite of all rays emerging from the source at 5° increments and calculated out to a 10^{-4} energy cutoff, does not show many rays reaching the surface in the valley and those that do were determined from the printout of data to have emerged from the source at angles of 130° and 150° from the vertical (see p. 57). So few rays appearing in Las Vegas Valley can be accounted for by (1) the westward dip of Paleozoic rocks under the valley, (2) the number of interfaces that the rays must cross to reach the surface, or (3) the number of interfaces crossed by rays enroute to the Paleozoic rocks under the valley.

The westward dip of the rocks causes some rays from the source, which are reflected off the M or Conrad discontinuities, to intersect high velocity Paleozoic rocks, SOEd-7, PIPMDS1-6, at angles greater than the critical angle. Such totally reflected rays continue on southeastward and do not emerge at the surface in Las Vegas Valley.

The energy output resulting from an incident ray at a number of parallel elastic boundaries depends upon the number of the elastic boundaries crossed by the partitioned and transmitted rays; it is presumed that the initial angle of incidence is the same for all cases examined. From the subsurface at Las Vegas Valley seismic rays have to cross seven to eight elastic boundaries in contrast to four or five at most other places in the model. In addition, the same sort of "shielding" effect may occur in unit Tc-3, as occurred in unit Tb-3 under Ralston Valley in the Toiyabe model. As very few rays reached unit Tc-3, however, the model neither confirms nor denies this supposition. Another reason for the lack of rays in Las Vegas Valley is that most rays reaching the base of the Paleozoic rocks under the valley had been reflected several times off the M and Conrad discontinuities with a loss of energy, due to partitioning, at each reflection.

Southeast of Las Vegas Valley, the rocks are predominantly intrusive and extrusive. Contacts are few because of few changes in physical properties. Also contacts are irregular. Seismic rays that reach these igneous rocks continue through to the surface because they are not reflected downward nor are they attenuated as much as the rays that cross the many interfaces underlying Las Vegas Valley.

Though a rigorous correlation cannot be made, the greater concentration of rays shown in the model (fig. 8b) southeast of Las Vegas Valley may be in part substantiated by the seismic records obtained along a line from Nevada Test Site to Kingman, Ariz., that has been described by Diment, Stewart, and Roller (1961). Among other strong late arrivals in

their records, they noted some distinctive phases (1961, p. 209) at distances of about 200-400 kilometers. They designated these as X phases and described them as "characterized by a rather sudden onset of waves of much higher amplitude than those preceding them". The ray plot (fig. 8b) shows that at distances of more than about 650,000 feet (about 200 kilometers) from the source, the rays that reach the surface have been reflected many times within the crust. Their arrival times, as calculated by the computer program, is about 33 seconds. The X phases also arrived in 33 seconds at a distance of 200 kilometers, in the seismic records. According to Diment, Stewart, and Roller (1961, p. 210) the travel time of the X phases required an apparent velocity of about 6 kilometers per second. The ray plot indicates that a layer with such a velocity is not necessarily the explanation of the late arrivals. Another explanation suggested by these authors is that their X phase may be a " P_1 wave reflected once from the earth's surface" (1961, p. 211). The ray plot tends to confirm the latter interpretation because rays reaching the surface beyond 650,000 feet (~ 200 km) have been reflected between interfaces many times.

Figures 9a, 9b, 9c, and 9d show calculated displacements along the Las Vegas model. The displacements were calculated for angular increments at the source of 20° but the initial ray for each figure is 5° more from the vertical than the preceding figure. In this manner, the composite (fig. 8c) of all of the figure 9 illustrations is in effect a plot of rays originating at the source at angular increments of 5° . The energy-cutoff level for all plots was 10^{-4} . This method of plotting

is an economical way of obtaining the distribution of rays reaching the surface along the model for small angular increments at the source. If these rays were plotted as a ray plot diagram, the time required for the plotting by the methods presently available would be excessive. The most significant information provided by figures 9a-9d is that the rays emerging in Las Vegas Valley can be determined to have been generated by rays emerging from the source at angles of 130° and 150° . Figure 9c shows rays intersecting the surface in Las Vegas Valley that are not present on any of the other figures. Examination of the printout of the information for the plot of figure 9c, reveals that the rays intersecting the surface in Las Vegas Valley originated at the source at angles of 130° and 150° . It can be inferred, then, that a small change in the angle at which a ray emerges from the source may make a large change in the distribution of rays at great distances, depending upon the distribution of elastic units near the source.

COMPARISON OF NORMALIZED AND CALCULATED DISPLACEMENTS

As the computer programs calculate ray paths and ground motion on the basis of ray theory and a realistic geological model, the calculated results of the programs must be tested by comparison with some recorded seismic measurements. A comparison is made between the vertical displacements calculated by the computer program and a few vertical displacements derived from seismic records. The comparison is crude and not analyzed statistically for lack of enough suitable measured displacements.

A common method of analyzing a group of seismic measurements with respect to predictability is to compare them to standard curves derived by a least-squares fit to previous measurements. Such curves, representing amplitude of acceleration, velocity, or displacement as a function of distance from the source, have been used by the Environmental Research Corporation (ERC) to analyze the seismic measurements made for some nuclear events and to make predictions of ground motion. Statistical measures of predictability can be obtained, but they are only applicable to seismic signals generated, propagated, and received at the same locations for every set of measurements. The standard curves cannot be adjusted for particular geologic settings except in a gross way. Such adjustment is done by grouping the data according to the general geologic setting of the source signal, and by one of two types of rock, alluvium or hardrock, on which the seismometers receiving the signals were placed. This statistical method of prediction is very useful and adequate for predicting seismic response at particular locations, provided enough empirical data are available from which curves can be derived.

The seismic ray path method provides calculated values for a unique geologic model; these values are not amenable to statistical analysis; that is, calculated values at a particular location cannot be compared rigorously to a smoothed prediction curve derived by a least-squares treatment of seismic measurements. A useful comparison of the displacement calculated by the seismic ray path method to actual measured displacement can be made by the following steps:

1. Plotting the displacements of rays emerging at the surface along the Toiyabe and Las Vegas lines of section (figs. 7c and 8c).
2. Normalizing some measured displacements to calculated displacements.
3. Comparing the normalized displacements to calculated displacements at the location of the seismic stations as projected to the geologic models.

Figures 7c and 8c show the vertical displacements for rays intersecting the ground surface along the Las Vegas and Toiyabe models; these figures also show normalized measurements (table 1) of vertical displacements at a few seismic stations along the lines of section. The normalized displacements are based upon seismic data in an ERC report on the analysis of seismic data recorded from the Greeley event (Davis, 1967, tables 3 and 4). These particular data were selected because Greeley was one of the events nearest to UE20f, and more seismic stations were located on or near the lines of the geologic models than for any other event. Most of the displacements^{1/} used for normalizing are derived from velocity meter or accelerograph measurements; furthermore, they are reported to be the maximum motions recorded at each station. The recorded vertical displacements were normalized to compare with the computer program displacements by calculating a factor required to equate the vertical displacements recorded at station T-4 to the program-calculated displacement at T-4. This latter displacement was obtained from the computer printout for the distance of T-4 from UE20f.

^{1/}The data tabulated in the ERC report are not given here in order to avoid classifying this report.

Table 1.--List of normalized vertical displacements

Station	Normalized vertical displacement
Mercury	6.08×10^{-9}
SE-2	2.26×10^{-9}
SE-4	4.28×10^{-9}
Las Vegas (1st National Bank)	2.81×10^{-9}
North Las Vegas	1.13×10^{-8}
Las Vegas (Dunes)	2.63×10^{-9}
Las Vegas (SE-6)	2.80×10^{-9}
T-4	Used to obtain normalizing factor
T-5	6.08×10^{-9}
Tonopah (motel)	1.95×10^{-9}
Tonopah (church)	1.78×10^{-9}
Beatty (alluvium)	9.10×10^{-9}
Beatty (hardrock)	8.34×10^{-9}

Inspection of figures 7c and 8c indicates that the normalized displacements are near the apparent median value of the calculated displacement. The seismic data, however, are too scant for considering the comparison as anything more than suggestive evidence of prediction capability. Furthermore, as mentioned earlier in this report, the seismic data are theoretically not suitable because the source and most stations on which the seismic data are based are not actually in the geologic models.

DISCUSSION

On the basis of comparison of ray path densities and calculated displacement amplitudes with a few measured displacement amplitudes, the program may be used to estimate the relative ground motion to be expected from explosions in new test areas, or in areas where the application of nuclear explosives for peaceful uses is to be tried. An example of this use of the program in its present untested form is that a qualitative estimate can be made of the effect of moving an explosion source closer to Tonopah, Nev., than present explosion sources in Pahute Mesa.

As pointed out in the discussion of the Toiyabe ray plot, Booker Mountain and Tonopah are located in a zone where many rays reach the surface by reflection off the Conrad and M discontinuities. Furthermore, a zone with relatively few rays termed "shadow zone" occurs between the source and Booker Mountain. If the source were moved about 100,000 feet towards Booker Mountain, fewer rays should reach the surface in the vicinity of the mountain because it would be approximately within the shadow zone.

Some evidence pertinent to the effect of moving an explosion source closer to Booker Mountain supports the reasoning that zones of high ray densities are zones of high ground motion. For example the ground motion at Beatty is shown to be less than predicted by ERC equations (Davis, 1967, figs. 3, 4, 5, 6, and 7). Furthermore, for one event in Pahute Mesa (Halfbeak) the acceleration recorded at Beatty was actually less than at Tonopah (Davis, 1967, p. 22) even though Tonopah is over twice as far from the mesa as Beatty. An explanation of the anomalously little ground motion at Beatty may be that if a hypothetical Beatty is plotted at Beatty's distance (155,000 feet) from UE20f on the Toiyabe ray plot, the shadow zone is directly under the hypothetical Beatty. Local, near-surface geology may, of course, preclude the assumption that Beatty would receive the same number of rays as the hypothetical Beatty, but the probability is high that Beatty is over a shadow zone because the depth of the Conrad and M discontinuities, which control the shadow zone, do not change appreciably in so short a horizontal distance.

If the above data and reasoning are correct, the obvious conclusion is that ground motion at Tonopah would be reduced by locating explosion sites closer to it.

SUMMARY AND CONCLUSIONS

Ray path analysis, based on ray theory and numerical solution of Zoeppritz' equations, and utilizing high-speed computer technique, now can be applied to realistic geologic models rather than highly simplified models. Calculation of the ray path provides the following information for an emerging ray intersecting the earth's surface: Horizontal and vertical coordinates of the point of emergence, angle of incidence, ray type (P or S), energy, phase angle, distance and time of travel from the energy source (explosion) to the emergent point, and the amplitude of vertical and horizontal components of relative ground motion at the point of emergence.

Comparison of calculated values of the amplitude of vertical displacement with measured values at a few seismic stations on or near the alinement of the two geologic models selected for their study shows a reasonable fit. Further, anomalous displacement values measured at some seismic stations for explosions at NTS appear to be explained, as these values are in accord with calculated values based on a realistic geologic model.

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