Fortran Program for Generation of Synthetic Seismograms

By ALBERT J. RUDMAN and ROBERT F. BLAKELY

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Fortran Program for Generation of Synthetic Seismograms

By ALBERT J. RUDMAN and ROBERT F. BLAKELY

GEOPHYSICAL COMPUTER PROGRAM 2

DEPARTMENT OF NATURAL RESOURCES
GEOLOGICAL SURVEY OCCASIONAL PAPER 13

PRINTED BY AUTHORITY OF THE STATE OF INDIANA
BLOOMINGTON, INDIANA: 1976
To the Geophysics Community
This report is one of a series of Geophysical Computer Programs that will be published in the Indiana Geological Survey Occasional Paper Series. Members of the geophysics section of the Indiana Geological Survey, with the advice and counsel of an advisory board,* will select and edit submitted papers. At present, programs dealing with the calculation of gravity and magnetic fields over two- and three-dimensional bodies, depth calculations from seismic refraction data, digital filtering, and cross correlation and convolution processes are in preparation. Readers are invited to submit programs and manuscripts to the geophysics section. The primary purpose of this series will be to make readily available those programs that deal with established geophysical computations.

Although the editors of some journals solicit only new approaches, we will seek to publish programs that also deal with standard and classic problems. Our experience has shown that geophysicists, working alone or at relatively small laboratories, do not always have access to such programs. We also solicit programs implementing new geophysical procedures, but we anticipate that such material will be made available only rarely. Nevertheless, even large laboratories with extensive computer libraries may welcome a study of the other fellow's approach. In the same spirit, we hope that geophysicists will share both their new and standard programs.

The format for this series is intentionally kept simple to encourage others to submit manuscripts. It should contain: (1) a statement to establish the purpose of the program and some discussion of applications; (2) a brief summary of the theory that underlies the algorithm; (3) a discussion of the program, perhaps with the aid of a flow diagram; and (4) presentation of a test case.

Responsibility for distribution of the program cards or furnished tapes will be assumed by the Indiana Geological Survey.

—Albert J. Rudman and Robert F. Blakely, editors

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*Norman S. Neidell, Geoquest International; Sigmund Hammer, University of Wisconsin; Daniel F. Merriam, Syracuse University; Judson Mead, Indiana University; and Franklin P. Prosser, Indiana University.
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Foran Program for Generation of Synthetic Seismograms

By ALBERT J. RUDMAN and ROBERT F. BLAKELY

Abstract
A FORTRAN IV computer program to generate synthetic seismograms has been developed by using reflection coefficients computed for layers with differing velocities $v$. Convolution of coefficients with an input wave yields the synthetic seismogram. Choice of the input wave depends on what the user considers to be the best approximation of the response of his seismic system to a reflection.

Input to the program consists of depths and interval transit times digitized from a continuous velocity log. Output consists of (1) a table of depths, transit times, average vertical velocities, two-way travel times, interval velocities, reflection coefficients, and amplitudes of the synthetic seismogram and (2) line-printer and Calcomp plots of the input wave and seismogram. Although this program is applicable in most geologic situations, there is no provision for including multiple reflections or energy attenuation.

Introduction
Mapping of buried geologic features by the seismic reflection method depends on measurements of seismic waves reflected from bedding planes. According to elastic theory, reflections originate at the interface of layers that exhibit a contrast in density $d$ and seismic velocity $v$. The ratio of the amplitudes of the normally incident plane longitudinal wave and the reflected longitudinal wave is given by reflection coefficient $\text{REFC}$

$$\text{REFC} = \frac{d_i + 1 \frac{v_i + 1}{v_i} - d_i \frac{v_i}{v_{i+1}}}{d_i + 1 \frac{v_i + 1}{v_i} + d_i \frac{v_i}{v_{i+1}}} \approx \frac{v_{i+1} - v_i}{v_{i+1} + v_i} \tag{1}$$

Subscripts identify layers above and below the interface. For most layers, the density does not change markedly and the reflection coefficient depends principally on changes in velocity.

For a study of geologic structures and stratigraphic facies changes, reflections are usually traceable from one seismogram to another, and corresponding geologic structures can be inferred. Identification of a specific stratigraphic unit as the source of some observed reflections is difficult. One approach is to model variations of vertical velocity within the stratigraphic section and use a computer to create a synthetic seismogram for that sequence of rocks. Reflections can be related to particular stratigraphic units by comparing a seismogram made in the field with its synthetic seismogram.

Stratigraphic changes also can be studied in this manner. For example, a layer of sandstone overlying a limestone may produce a reflection having form and amplitude different from that of a reflection originating from shaly sandstone over the same limestone. A change in thickness of individual strata may also affect the form and amplitude of the reflection. These changes in form and amplitude can be seen on synthetic seismograms because velocities and thicknesses of layers comprising the model are varied.

Theory
Continuous velocity logs (fig. 1A) provide data to model velocity changes in a given area. In this study CVL’s were usually digitized at 2-foot intervals. Because the CVL records transit times (tt) in microseconds per foot, multiplication by sampling interval yields travel time for that interval. Two-way travel times are summed to make units of a millisecond of time. Average interval transit times are then computed for each millisecond interval (fig. 1B). These transit times are used to compute reflection coefficients at millisecond intervals by using equation 1 together with the relation that $v = 1/\text{tt}$ (fig. 1C). The resulting train of coefficients would be a valid synthetic seismogram if the reflected seismic signal was approximated by a simple pulse or spike. But the combined impulse response of the earth and recording instruments modifies the signal to an extended waveform. Convolution of this waveform with the reflection coefficients therefore yields the synthetic seismogram (fig. 1D).

1Dr. Rudman is associate professor of geophysics at Indiana University. Dr. Blakely is a geophysicist of the Indiana Geological Survey and associate professor in the department of geology at Indiana University.
Amplitudes of reflections are predominately controlled by reflection coefficients, which in turn are a measure of contrast in interval velocities. In practice, impulse response of the earth and instruments is quite different from the simulated waveform used as an illustration in figure 1. Actual waveforms may extend for 100 milliseconds, and reflections are therefore a composite of overlapping waveforms. Convolving even a short (4-millisecond) input wave with only three reflection coefficients yields a complex seismogram (fig. 2).

Program SYNSEIS (described in the next section) follows the general theory described above. In developing a test case for this program, Biggs, Blakely, and Rudman (1960) assumed that the response of a geophone to a seismic pulse had the form shown in figure 3A. This wave was simulated on an analog computer and introduced into a set of seismic instruments. Instrument settings (band pass of 70-92 hz) duplicated those used in obtaining a seismogram near a deep test well in central Indiana. Response of the seismograph to the simulated wave is shown in figure 3B. It is this type of waveform that must be convolved with the reflection coefficient train to obtain the synthetic seismogram.

A CVL of the Brown well in central Indiana provided velocity data necessary to test the algorithm and program SYNSEIS. Transit times and the corresponding depths were digitized at 2-foot intervals and converted at 1-millisecond intervals to average interval velocities in feet per second (fig. 4). Total travel time required for a wave to reach a depth yields the average vertical velocity plotted in the figure. Reflecting horizons are expected at major velocity changes observed at the top of the Devonian limestone, at the top of the Trenton Limestone, and near the top of the Eau Claire Formation. A synthetic seismogram (fig. 5) was generated from this CVL by using the input wave shown in figure 3B.

A field seismogram was recorded 0.6 mile east of the Brown well. Four traces from this record are reproduced in figure 5 for comparison with the synthetic seismogram. (The synthetic seismogram trace is duplicated four times to accent the similarities in the two records.) Comparison of the records shows close correlation for such prominent reflection
Figure 2. Convolution of an input wave (seismograph response) with three reflection coefficients to yield a synthetic seismogram.
groups as the Trenton Limestone, lower part of the Knox Dolomite, the Mount Simon Sandstone, and the metasedimentary rock unit near the top of the basement complex. Similarities in these reflection groups indicate that the input waveform was a realistic approximation. Study of these two records can also provide insight into the geologic nature of reflections and limitations of the algorithm. Some examples follow.

One of the most prominent reflections on these records is that originating from small velocity contrasts within the metasedimentary unit. This unexpected result demonstrates that a large velocity contrast is not necessary to generate major reflections.

The weak reflections on the field seismogram at 0.12, 0.30, and 0.64 seconds are not represented by comparable events on the synthetic record and therefore may represent multiple reflections. Program SYNSEIS does not generate multiple reflections and this limits the applicability of the algorithm.

Program SYNSEIS does not include attenuation factors and this may explain why reflections from the upper part of the Knox Dolomite and the Eau Claire Formation appear to be more prominent on the synthetic record than on the field seismogram. The reflection observed on the synthetic record may be absent on the field seismogram because of attenuation or cancellation with interfering multiple energy.

The algorithm for program SYNSEIS was presented in previous papers by Peterson, Fillipone, and Coker (1955), Durschner (1958), and Biggs, Blakely, and Rudman (1960). Although they are based on numerous assumptions, the synthetic seismograms produced generally agree well with field seismograms. For some the agreement is poor, and more complex approaches have been developed to include multiples and transmission coefficients (Wuenschel, 1960) as well as frequency and depth attenuation factors (Trorey, 1962). These latter techniques involve matrix formulation for computing the reflected signal at the surface of a multilayered half-space due to a normally incident plane wave. Computational times may be long for geologic sections.

In summary, program SYNSEIS has the advantage of simplicity and short run times. Although multiple reflections and attenuation factors are not incorporated into our algorithm, this limitation is not considered a major problem. In general, when multiples are incorporated into synthetic seismograms, these multiples are greater than those observed on field records (Wuenschel, 1960). Trorey (1962) suggested that attenuation factors may reduce the multiple content.

Algorithm for Program SYNSEIS
(See appendix 1)

1. Input Parameters (See appendices 2 and 3)

Read in identification cards of input wave (INPUT); digitized amplitudes (WAVE(k)); identification card of CVL or velocity model (NAME); parameter card with initial depth (Z(1)); initial transit time (X(1)), depth increment in feet (INC), and number of time lines per inch to be plotted on final output (NLINES); depths (Z(i)) and transit times (X(i)) from a CVL or model.

A generalized flow of program SYNSEIS (appendix 1) is given in these sections and illustrated in a flow diagram (appendix 2). The first operation involves reading the parameters summarized above. Amplitudes for the input wave must be digitized at millisecond intervals and should not exceed 200 milliseconds total time. If the CVL is digitized at regularly spaced intervals (described by the parameter INC), depths need not be entered on succeeding cards. If irregular intervals are used, then the product ((interval in feet) X (transit time in seconds per foot)) must be less than .001 second. Final output includes a Calcomp plot of the synthetic seismogram. The user can choose NLINES (the number of time lines per inch) to match available field records. The final input cards are depths and transit times from a CVL or velocity model. For convenience in identification, all data cards are coded in column 1 with 1 for the input wave and 2 for transit times.
Figure 4. Interval and average vertical velocities computed from transit times of a continuous velocity log in central Indiana. From Biggs, Blakely, and Rudman, 1960, fig. 2.
2. Calculate and Print Output

Calculate average velocity (AVEV), interval velocity (XINTV), two-way travel time (TTIME(J)), reflection coefficients (REFC(J)), and amplitude of final output seismogram (OUTPUT(J)).

Two-way travel time in seconds is computed for each interval of transit time. If computed time has not increased by a full millisecond, average vertical velocity to that interval is computed, and depth, transit time, and average velocity are printed.

If two-way time has increased a full millisecond, a subroutine (SSALC) is called to calculate amplitude of the output wave for the given two-way time. The reflection coefficient is computed from equation 1 by using interval transit times. The input wave is then multiplied by the reflection coefficient and added to previous values stored in an array (AMPL). The first value in this array is amplitude of the convolved waveform to be plotted as the synthetic seismogram. After storing this first value (OUTPUT), convolution is completed by shifting all values in AMPL up one unit in the array. Depth, transit time, average velocity, interval velocity, two-way time, reflection coefficient, and convolved wave amplitude are then printed.

3. Plot Results

The input wave (INPUT) and synthetic seismogram (OUTPUT) are plotted on line printer and Calcomp plotter.

Subroutine LINEPT plots input wave and synthetic seismogram data on a line printer using asterisks. Values after the last reflection coefficient are not a valid part of the seismogram, although they may be of some interest. A plus sign is substituted for the asterisk to alert the user.

Subroutine SEISPT plots input wave, CVL, and seismogram by using a Calcomp incremental plotter. All calls are Calcomp compatible. Identification of input wave and CVL is printed beneath the X-axes. Time lines on the seismogram are drawn every 10 milliseconds of two-way travel time. Depths corresponding to two-way times are also printed on the seismogram. Depths are omitted in the final portions to alert the user that data are after the final reflection coefficient.

Concluding Statement
Program SYNSEIS is reproduced in appendix 1. Appendix 2 is a generalized flow diagram of the main calling program. Appendix 3 lists input cards used to run the test case. Appendices 4-7 reproduce portions of the output of the test case: a synthetic seismogram generated from CVL data of the Brown well in central Indiana. Running time on a CDC 6600 was 24 seconds for 3,100 transit times. A maximum of 3,500 transit times requires 64 K octal words of computer space (60 bit-word size).

We thank Paul Friesen, who modified the output of the original program and improved efficiency in running time and space requirements. Special acknowledgments are extended to Indiana University’s Wrubel Computing Center for the use of its facilities.
GEOPHYSICAL COMPUTER PROGRAM 2

Literature Cited

Biggs, M. E., Blakely, R. F., and Rudman, A. J.
1960 - Seismic velocities and synthetic seismogram computed from a continuous velocity log of a test well to the basement complex in Lawrence County, Indiana: Indiana Geol. Survey Rept. Prog. 21, 15 p., 4 figs.

Durschner, H.

Peterson, R. A., Fillipone, W. R., and Coker, F. B.

Trörey, A. W.

Wuenschel, P. C.
Appendix 1. Fortran IV Program SYNSEIS

The program contains numerous comment cards calling program is followed by seven subroutines. identifying the purpose of each section. The main

```fortran
PROGRAM SYNSEIS(INPUT,OUTPUT,PLOT,TAPE1=INPUT,TAPE2=OUTPUT.
   1,TAPF5=PLT)

- PROGRAM SYNSEIS GENERATES A SYNTHETIC SEISMGRAM FROM AN INPUT
- WAVE OF THE USERS CHOICE AND A VELOCITY MODEL OF THE EARTH. THE
- INPUT WAVE IS DIGITIZED AT ONE MILLISECOND INTERVALS. THE
- VELOCITY MODEL IS DIGITIZED USUALLY AT REGULAR INTERVALS FROM
- A CONTINUOUS VELOCITY LOG (CVL). IT CONSISTS OF DEPTH IN
- FEET AND CORRESPONDING TRANSIT TIME IN MICROSECONDS PER FOOT.
- THE RECOMMENDED DIGITIZING INTERVAL IS TWO FEET BUT ANY INTER-
- VAL CAN BE SELECTED AS LONG AS THE RATIO (INTERVAL IN FEET)/(VELOCITY)
- IS LESS THAN .001.
- THE PROGRAM COMPUTES THE REFLECTION COEFFICIENTS AT ONE MILLI-
- SECOND INTERVALS OF TWO-WAY TRAVEL TIME. THIS TRAIN OF REFLECTION
- COEFFICIENTS IS THEN CONVOLVED WITH THE INPUT WAVE TO YIELD
- THE SYNTHETIC SEISMGRAM.
- OUTPUT OF THE PROGRAM CONSISTS OF A TABLE OF DEPTHS, TRANSIT
- TIMES, AVERAGE VERTICAL VELOCITIES, INTERVAL VELOCITIES, TWO-WAY
- TRAVEL TIMES, REFLECTION COEFFICIENTS AND AMplitudes OF THE
- SYNTHETIC SEISMGRAM. THE SEISMGRAM IS PRINTED ON THE LINE
- PRINTED ON A CALCOMP PLOTTER.
- ORDER OF DATA CARDS
- 1 TITLE CARD. DESCRIBES INPUT WAVE. FORMAT(8A10)
- 2 INPUT WAVE. COL 1 IS AN IDENTIFICATION CODE (=1).
- COLS 2-5 IS MAGNITUDE OF WAVE AT ONE MILLI-
- SECOND INTERVALS. MAXIMUM NUMBER OF CARDS IS
- 200. FINAL CARD IS FLAGGED WITH 999.
- FORMAT(11*F4.0)
- 3 TITLE CARD. DESCRIBES CVL USED FOR MODEL. FORMAT(8A10)
- 4 PARAMETER CARD. COL 1 IS AN IDENTIFICATION CODE (=2).
- COLS 2-5 IS INITIAL DEPTH. COLS 6-9 IS INITIAL
- TRANSIT TIME. COLS 10-13 IS DIGITIZING INTER-
- VAL OF DEPTH VALUES. IF A REGULAR INTERVAL IS
- USED, DEPTHS NEED NOT BE ENTERED ON SUCCEEDING
- CARDS. IF DEPTHS ARE TO BE READ FROM INPUT
- CARDS, A ZERO IS PLACED IN COLS 10-13. COLS
- 14-15 ARE THE NUMBER OF TIME LINES PER INCH TO
- BE DRAWN ON THE SEISMGRAM PLOT.
- FORMAT (11*F4.0,F4.1,F4.0,I2)
- 5 VELOCITY MODEL CARDS. COL 1 IS AN IDENTIFICATION CODE (=2).
- COLS 2-5 IS DEPTH. COLS 6-9 IS TRANSIT TIME.
- FINAL CARD SHOULD BE FLAGGED WITH A ZERO IN THE
- TRANSIT TIME. FORMAT(11*F4.0,F4.1)
- PROGRAM SYNSEIS: ORIGINALLY WRITTEN BY BIGGS, BLAKELY, AND RUDMAN
- (INDIANA GEOL. SURVEY REPT. OF PROGRESS NO. 21; 1960). THIS
- VERSION IS A MODIFICATION WRITTEN BY PAUL FRIESEN IN 1975 AT THE
- INDIANA GEOLOGICAL SURVEY UNDER THE DIRECTION OF AJ, RUDMAN
- AND R.F. BLAKELY
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NOR THE INDIANA UNIVERSITY DEPARTMENT OF GEOLOGY FOR ANY ERRORS,
MISTAKES OR MISREPRESENTATIONS THAT MAY OCCUR WHEN USING THIS
PROGRAM. NOR IS RESPONSIBILITY ASSUMED BY THE INDIANA UNIVERSITY
WRUEL computing center for its correct reproduction.

COMMON Z(3500),XI(3500)
DIMENSION INPUT(8),NAME(8),OUTPUT(1950),TTIME(1750)
DIMENSION REFC(1750),AMPL(200),WAVE(203),DEPTH(1750)
TYPE REAL INC
TYPE INTEGER OUTMAX
DATA SUMPRE,XINTG,AMPL,IMUMT/203*0.0/  
********************************************************************************
* READ AND PRINT INPUT DATA                                                     *
********************************************************************************
* READ IN TITLE OF INPUT WAVE (INPUT)                                           *
* READ (1,140) INPUT                                                           *
* READ IN IDENTIFICATION CODE (ITYPE) AND INPUT WAVE DATA (WAVE)                *
* BRANCH IF WAVE=999.                                                           *
* DO 10 K=1,200+1                                                               *
    READ (1,110) ITYPE,WAVE(K)                                                 *
    IF(WAVE(K),EQ.,999.,0) GO TO 20                                             *
* N AND FN ARE NUMBER OF DATA POINTS OF INPUT WAVE                              *
* N=K                                                                          *
* FN=N                                                                          *
* 10 CONTINUE                                                                  *
* SET NUMBER OF POINTS IN INPUT WAVE AND RESET SUBSCRIPTS                       *
* 20 INMAX=K-1                                                                 *
    I=1                                                                       *
    J=1                                                                       *
    K=1                                                                       *
* SKIP TO NEW PAGE, READ IN AND PRINT TITLE OF CONTINUOUS                       *
* VELOCITY LOG (NAME) AND PRINT TITLE OF INPUT WAVE                             *
* WRITE (2,100)                                                               *
    READ (1,140) NAME                                                         *
    WRITE (2,150) NAME                                                        *
    WRITE (2,130) INPUT                                                        *
* PRINT HEADINGS                                                               *
* WRITE (2,120)                                                               *
    WRITE (2,160)                                                            *
* READ IN PARAMETER CARD. CONTAINS IDENTIFICATION CODE (ITYPE).                *
* INITIAL DEPTH(Z), INITIAL TRANSIT TIME (XI), DEPTH INCREMENT                 *
* (INC), AND NUMBER OF TIME LINES PER INCH TO BE PLOTTED ON CALCOMP             *
* PLOT OF INPUT WAVE AND SEISMOMGRAM (NLINES). IF INC=ZERO, DEPTHS              *
* MUST BE READ IN FROM SUCCEEDING CARDS. IF NLINES=ZERO, NO TIME               *
* LINES WILL BE DRAWN, FORMAT(11,F4.0,F4.1,F4.0,12)                           *
* IF INC IS ZERO WE MUST READ IN THE DEPTHS INDIVIDUALLY                       *
* IF(INC,EQ.,0,0) GO TO 40                                                    *
APPENDIX 1

*-- READ IN TYPE AND TRANSIT TIME *
*-- DO 30 I=2,3497+1
    READ (1,220) I,TYPE,XI(I)
*-- TEST FOR LAST DATA CARD *
*-- IF(XI(1) .EQ. 0,0)GO TO 60
    Z(1)= Z(1-1) + 1NC
30 CONTINUE
*-- READ IN TYPE, DEPTH AND TRANSIT TIME *
*-- DO 50 I=2,3497
    READ(1,170) I,TYPE,Z(I),XI(I)
*-- TEST FOR LAST DATA CARD *
*-- IF(XI(1) .EQ. 0,0)GO TO 60
50 CONTINUE
*-- PRINT VALUES OF FIRST POINT *
*-- WRITE (2,210) Z(1),XI(1)
*-- CALCULATE AND PLOT OUTPUT VALUES *
*-- ************END OF PROGRAM ********************
*-- CALCULATE ONE-WAY TIME(SUMT) AND AVERAGE VELOCITY (AVEV) AND PRINT VALUES *
*-- ZPREV=Z(1)
*-- DO 80 I=2,OUTMAX
*-- CALCULATE ONE-WAY TIME *
*-- SUMT=SUMT+((XI(I)+XI(I-1))*(Z(I)-Z(I-1)))/2000
*-- BYPASS CALCULATION SEQUENCE IF TWO-WAY TIME HAS NOT INCREASED +1 *
*-- IF(2*SUMT-XINTG .LE. 0.5)GO TO 70
*-- CALL SSCALC(I,J,K,OUTMAX,ZPREV,TIME,REFC,WAVE,OUTPUT, DEPTH,SUMPRE,AMPL)
*-- XINTG=XINTG+1.0
*-- GO TO 80
70 AVEV=(Z(1)-Z(1))/1000/SUMT
*-- WRITE (2,180) Z(1),XI(1),AVEV
80 CONTINUE
*-- CALCULATE FINAL PART OF SEISMOGRAM *
*-- CALL UNCALC(J,INMAX,WAVE,OUTPUT,AMPL,TIME,DEPTH,REFC)
*-- CALL LINPLOT WHICH PLOTS INPUT WAVE AND SEISMOGRAM ON LINE *
*-- CALL SEISPLT WHICH PLOTS INPUT WAVE, CVL AND SEISMOGRAM ON *
*-- A CALCONE INCREMENTAL PLOTTED *
*-- STOP
**FORMATS**

100 FORMAT(I1,H1)
110 FORMAT(I1,F4,0)
120 FORMAT(1H,** TRANSIT AVE INT TWO-WAY **)
130 ** + *REFLECTION*)
140 FORMAT(1X,BA10//)
150 FORMAT(1X,BA10/)
160 FORMAT(1H,** DEPTH VELOC VELOC TIME **)
170 ** + *AMPL*)
180 FORMAT(I1,F4,0,0,F4,0,0,12)
190 FORMAT(1H,** F8,0,F8,1,F8,0)
190 FORMAT(1X,F8,0,F8,1,F8,0,F8,1,F8,1,F8,3,F12,6,F10,3)
200 FORMAT(1X,F8,0,44X,F10,3)
210 FORMAT(1H,** F8,0,F8,1)
220 FORMAT(I1,4X,F4,1)

END

SUBROUTINE SSCALC(I,J,K,SUMT,ZPREV,TTIME,REFC,WAVE, +
OUTPUT.DEPTH,SUMPTE,AMPL)

**-**

**-** SUBROUTINE CALCULATES AVERAGE VELOCITY (AVEV), INTERVAL VELOCITY
**-** (XINTV), TWO-WAY TIME (TTIME), REFLECTION COEFFICIENT (REFC),
**-** AND AMPLITUDE (OUTPUT) AT MILLISECOND INTERVALS. DEPTH (Z)
**-** AND TIME (X), AND THE ABOVE NAMED VARIABLES ARE THEN OUTPUT ON THE
**-** PRINTER. NOTE THAT THE CALLING PROGRAM ALSO OUTPUTS AND
**-** PRINTS INTERMEDIATE DEPTHS, TIMES, AND AVERAGE VELOCITIES
**-** BETWEEN MILLISECOND INTERVALS.

**-** COMMON Z(3500),XI(3500)
**-** DIMENSION TTIME(1),REFC(1),WAVE(1),OUTPUT(1),DEPTH(1)
**-** DIMENSION AMPL(1),XINTV(2)
**-** DATA SWITCH /0,0/;

**-** CALCULATE VELOCITIES AND REFLECTION COEFFICIENTS
**-** AT MILLISECOND INTERVALS

**-** CALCULATE AVERAGE VELOCITY (AVEV) FROM DEPTH (Z) AND ONE-WAY TIME (SUMT)
**-**
**-** AVEV=(Z(I)-Z(I-1))/1000/SUMT

**-** SET SUBSCRIPT VALUES TO BE USED WITH INTERVAL VELOCITY (XINTV)
**-**
**-** NEW=MOD(J+2)+1
**-** IOLD=MOD(J-1+2)+1

**-** CALCULATE INTERVAL VELOCITY (XINTV) FROM CORRESPONDING DEPTH INTERVAL AND TI
**-**
**-** XINTV(NEW)=((Z(I)-ZPREV)*1000)/(SUMPTE-SUMPTE)

**-** DOUBLE ONE-WAY TIME (SUMT) TO OBTAIN TWO-WAY TIME (TTIME)
**-**
**-** TTIME(J)=2*SUMT
**-** SWITCH=SWITCH+1

**-** BRANCH IF FIRST TIME THROUGH
**-**
**-** IF(SWITCH.EQ.1) GO TO 50

**-** CALCULATE REFLECTION COEFFICIENT (REFC)
**-**
**-** REFC(J)=(XINTV(NEW)-XINTV(IOLD))/(XINTV(NEW)+XINTV(IOLD))
*---------------------------------------------------------------
*                        AMPLITUDE CALCULATION SEQUENCE
*---------------------------------------------------------------

   DO 10 K=1,200+1
      IF(WAVE(K),EQ.,999,0) GO TO 20

*-- ADD CURRENT REFLECTION TO WAVE AMPLITUDE ARRAY (AMPL)
*--
   AMPL(K)=WAVE(K)*RFFC(J)+AMPL(K)
   10 CONTINUE
*--

*-- MOVE SUMMED WAVE AMPLITUDE TO OUTPUT ARRAY (OUTPUT)
*--
   20 OUTPUT(J)=AMPL(I)
   *--

*-- MOVE CORRECT DEPTH TO (DEPTH)
*--
   DEPTH(J)=Z(I)
**--

*-- OUTPUT ALL VALUES
*--
   WRITE(2,100)Z(I),Z(I),X(I),AVEV,XTNTV(NEW),TTIME(J),RFFC(J),OUTPUT(J)
**--

*-- MOVE AMPLITUDES UP ONE ELEMENT IN ARRAY AMPL(K)
*--
   DO 30 K=1,200+1
      IF(WAVE(K+1),EQ.,999,0) GO TO 40
         AMPL(K)=AMPL(K+1)
   30 CONTINUE
*--

*-- INCREMENT INDEX
*--
   40 J=J+1
*--

*-- PRESENT DEPTH AND TIME (Z(I) AND SUMT) BECOME LAST DEPTH AND
*-- TIME (ZPREV AND SUMPRE)
*--
   ZPREV=Z(I)
   SUMPRE=SUMT
   RETURN

*---------------------------------------------------------------
*                        INITIALIZATION SEQUENCE FOR FIRST TIME
*---------------------------------------------------------------

50    REFC(J)=0.0
   OUTPUT(J)=0.0
   DEPTH(J)=Z(I)
   GO TO 20

100   FORMAT(1X,F8.0,F8.1,F8.0,F8.0,F8.3,F12.6,F10,3)
   END
   SUBROUTINE UNCALC(J,INMAX,WAVE,OUTPUT,AMPL,TTIME,DEPTH,
                     + REFC)
   *-- SUBROUTINE CALCULATES POSSIBLE AMPLITUDES BASED ON FINAL
   *-- REFLECTION COEFFICIENT.
*--
   DIMENSION WAVE(1),OUTPUT(1),AMPL(1),TTIME(1),DEPTH(1)
   DIMENSION REFC(1)
*--
   PRINT INFORMATIVE MESSAGE THAT THE FOLLOWING AMPLITUDES ARE
   *-- NOT NECESSARILY ACCURATE
*--
   WRITE(2,100)
DO 10 K=1,INMAX
  ** MOVE AMPLITUDES TO (OUTPUT)
  **
  **  OUTPUT(J)=AMPL(K)
  **
  **  BBBBB, IS A FLAG TO INDICATE TO SUBROUTINE LINEPLT WE ARE IN
  **  FINAL PORTION OF SEISMOGRAM.
  **
  **  DEPTH(J)=BBBBB.
  **
  **  INCREMENT TWO-WAY TIME (TTIME)
  **
  **  TTIME(J)=TTIME(J-1)+1.0
  **
  **  ZERO OUT REMAINING REFLECTION COEFFICIENTS (REFC)
  **
  **  REFC(J)=0.0
  **  J=J+1
  **
  ** PRINT AMPLITUDES
  **
  **  WRITE(2*,110)AMPL(K)
  **
  ** CONTINUE
  **
  ** RETURN
  **
10  CONTINUE
  **
**------------------------------------------------------------------------
** FORMATS
**------------------------------------------------------------------------
100 FORMAT(4X*,DATA ENDS HERE,
  ** + 4X*,ORIGINATE FROM THE FINAL REFLECTION COEFFICIENT*,
  ** + 4X*,AND ARE NOT NECESSARILY A VALID PART OF THE*,
  ** + 4X*,SYNTHETIC SEISMOGRAM*)
110 FORMAT(5X*,F10.3)
  **
**
** SUBROUTINE LINEPLT INPUT WAVE AND THEN PLOTS SYNTHETIC SEISMOGRAM
** ON LINE PRINTER USINGASTERISKS TO SIMULATE THE PLOT. ON THE
** FINAL PORTION OF THE SYNTHETIC SEISMOGRAM PLUSES ARE SUBSTITUTED
** FOR ASTERISKS.
**
  ** TYPE INTEGER PLOT,FROM
  ** DIMENSION [INPUT(8),WAVE(200),NAME(8),OUTPUT(1950),
  ** + REFC(1750),FORM(4),PLOT(3),DEPTH(1750),TTIME(1)]
**------------------------------------------------------------------------
** INPUT PLOT SEQUENCE
**------------------------------------------------------------------------

WRITE (2*,110)
WRITE (2*,120) INPUT

** FIND MAXIMUM (XMAX) AND MINIMUM (XMIN) OF INPUT WAVE (WAVE)
**
  ** JMAX=J-1
  ** KMAX=K-1
  ** XMAX=AMAX(WAVE+KMAX)
  ** XMIN=AMIN(WAVE+KMAX)
**
** PLOT INPUT WAVE (WAVE) ON PRINTER
**
  ** PPLT(1)=BH(X*,
  ** PPLT(3)=8H1HM*)
**
** SCALE DATA TO FIT IN 75 SPACES
** Const=75/(XMAX-XMIN)
DO 10 K=1,KMAX+1
*
* NSPACE IS NUMBER OF SPACES BEFORE ASTERISK
NSPACE=(WAVE(K)-XMIN)*CONST
ENCOD(8*100,PPL(2))NSPACE
10 WRITE (2,PPL(2)) NSPACE
WRITE (2,110)
WRITE (2,120) NAME
WRITE (2,140) INPUT
WRITE (2,150)

******************************************************************************
** SEISMOGRAM PLOT SEQUENCE
******************************************************************************
*
** FIND MAXIMUM (XMAX) AND MINIMUM (XMIN) OF SEISMOGRAM (OUTPUT)
**
XMAX=AMMAX(OUTPUT,JMAX)
XMIN=AMMIN(OUTPUT,JMAX)
*
** PLOT SEISMOGRAM (OUTPUT) ON PRINTER
**
FORM(1)=BH(X,F5,F7)
FORM(2)=BH(2,F5,F7)
FORM(4)=BH(1,F7)
*
** SCALE DATA TO FIT IN 75 SPACES
CONST=75/(XMAX-XMIN)
DO 20 J=1,JMAX+1
*
** NSPACE IS NUMBER OF SPACES BEFORE ASTERISK
NSPACE=(OUTPUT(J)-XMIN)*CONST+2
ENCOD(8*100,PFORM3)NSPACE
*
** TEST FOR FLAG INDICATING FINAL PORTION OF SEISMOGRAM
IF(DPDEPTH(J)EQ8888)GO TO 30
WRITE (2,FORM) DEPTH(J),REFC(J),TTIME(J)
20 CONTINUE
*
** SEQUENCE FOR PLOTTING FINAL PORTION OF SYNTHETIC SEISMOGRAM
**
30 FORM(1)=BH(6X,F7)
*
** CHANGE ASTERISK TO PLUS
**
FORM(4)=BH(1,F7)
DO 40 I=J,JMAX
NSPACE=(OUTPUT(I)-XMIN)*CONST+2
ENCOD(8*100,PFORM3)NSPACE
WRITE (2,FORM) REFC(I),TTIME(I)
40 CONTINUE
WRITE (2,110)
RETURN
******************************************************************************
** FORMATS
******************************************************************************
100 FORMAT(18)
110 FORMAT(1H1)
120 FORMAT(1X,BA10/)
130 FORMAT(BA10)
140 FORMAT(1X,BA10//)
150 FORMAT(1H,DEPACT R,C, TIME*)
END
SUBROUTINE SEISPLT(L,N,NPTS,INPUT,WAVE,NAME,OUTPUT,TTIME,+
    DEPTH,OUTMAX)
*--  SUBROUTINE PLOTS INPUT WAVE, CONTINUOUS VELOCITY LOG (CVL),  
*--  AND SYNTHETIC SEISMOGRAM ON A CALCOPM INCREMENTAL PLOTTER  
*--
*--  COMMON Z(3500),XI(3500)  
COMMON/PLOTS/TIMLIN(200),TIME2(300)  
TYPE INTEGER HEADING,TITLE,DLABEL,TITLE2,OUTMAX  
DIMENSION WAVE(1),TTIME(1),OUTPUT(1),DEPTH(1),INPUT(1),NAME(1)  
DIMENSION TITLE(5),DLABEL(2),HEADING(5),ZTIME(400),YDASH(75)  
EQUIVALENCE(ZTIME(1),TIMLIN(1))  
ENCOD(25,200,TITLE)  
ENCOD(50,201,HEADING)  
ENCOD(50,202,DLABEL)  
ENCOD(10,203,TITLE2)

*--  INITIALIZATION SEQUENCE  
*--  ******************************************************************
*--
PTS=FLOAT(NPTS)  
*--
*--  SET UP X-AXIS  
*--
   TIME2(1)=0.0  
   DO 10 JK=1,N+1  
    TIME2(K)=TIME2(K-1)+1  
10  CONTINUE  
DIV=31.25  
   CALL IDENT(5,3HAJR)  
   CALL LIMIT(100,*)  
*--
*--  SET UP DASHED LINES  
*--
ZY=0.1  
   DO 20 JK=1,N+1  
    ZJK=FLOAT(JK)  
    YDASH(JK)=1.0+ZY*ZJK  
20  CONTINUE  

*--  ******************************************************************
*--  INPUT WAVE PLOT SEQUENCE  
*--  ******************************************************************
*--
*--  SCALE INPUT WAVE FOR X-AXIS 4.5 INCHES LONG AND Y-AXIS  
*--  2.0 INCHES HIGH  
*--
   CALL SCALE (TIME2(4)5+N+1,DIV)  
   DIV=20  
   CALL SYMSCLE(WAVE,2.0,2.0,N)  
   TIME2(N+2)=40.0  
*--
*--  DRAW X AND Y AXES  
*--
   CALL AXIS(1,0,6.5,TITLE2,10,2.0,90.0,WAVE(N+1),WAVE(N+2))  
   CALL AXIS (1,0,6.5,4HTIME, -4,4.5,0.0,TIME2(N+1),TIME2(N+2))  
*--
*--  WRITE WAVE TITLE  
*--
   CALL SYMBOL(1,0,5.8,0.1,OUTPUT,0.0,80)  
*--
*--  PLOT INPUT WAVE  
*--
   CALL LINE(1,0,6.5,TIME2,WAVE,N+1,0.0,0.0)  
*--
*--  DRAW DASHED VERTICAL LINES--PTS INDICATES NUMBER OF LINES PER INCH  
*--  BRANCH IF NO DASHED LINES TO BE DRAWN  
*--
IF(PTS.LT.1.0) GO TO 50
JMAX=INT(PTS*3.5)
DO 40 J=1,JMAX
   TIMLIN(J)=1.0+FLOAT(J)/PTS
DO 30 JN=56,74,2
   CALL PLOT(TIMLIN(JN)*YDASH(JN),3)
   CALL PLOT(TIMLIN(JN)*YDASH(JN+1),2)
30 CONTINUE
40 CONTINUE

* - WRITE TITLE OF PLOT
* -
   CALL SYMBOL(1.5,9.5,0.30,10*INPUT WAVE*0.0*10)

* - CVL PLOT SEQUENCE
* -
* - SET AXIS LENGTH AT NINE INCHES
50
AXLEN=9.0
*
* - SCALE CVL FOR X AXIS 9 INCHES LONG AND Y-AXIS 3 INCHES HIGH
   CALL SCALE(Z,AXLEN*OUTMAX+1,10,0)
   CALL SCALE(XI,3.0,OUTMAX+1,10,0)
*
* - DRAW X AND Y AXES
* -
   CALL AXIS(7.5,6.5,5,SHDEPTH,-5,AXLEN,0.0,0,Z(OUTMAX+1),Z(OUTMAX+2))
   CALL AXIS(7.5,6.5,5,12HTRANSIT TIME,12.2,0,90.0,XI(OUTMAX+1))
       + XI(OUTMAX+2))
*
* - PLOT DEPTH (Z) VS TRANSIT TIME (XI)
* -
   CALL LINE(7.5,6.5,7,XI,OUTMAX+1,0,0,0,0)
*
* - WRITE TITLE OF VELOCITY LOG
* -
   CALL SYMBOL(7.5,6.8,0.1,NAME,0,0,80)
*
* - WRITE TITLE ON PLOT
* -
   CALL SYMBOL(11.5,9.5,0.30,3HCVL,0.0,3)

* - SEISMOGRAM PLOT SEQUENCE
* -
* - PLOT SEISMOGRAM BELOW INPUT WAVE WITH VARIABLE LENGTH X-AXIS 40 PTS/INCH
* - AND Y-AXIS 4.5 INCHES HIGH
* -
   DIV=10,*0
   CALL SCALE(TTIME,30.0,L+2,1,0.0)
   TTIME(L+2)=10.0
   AXLEN=FLOAT(L)/TTIME(L+2)
   CALL SYMCLASS(OUTPUT,2,0,3,0,L)
*
* - PLOT X AND Y AXES
* -
   CALL AXIS(1.0,1.0,TITLE,25.3,0,90.0,OUTPUT(L+1),OUTPUT(L+2))
   CALL AXIS(1.0,1.0,heading,-50,AXLEN,0.0,TTIME(L+1),TTIME(L+2))
*
* - PLOT SEISMOGRAM
* -
   CALL LINE(1.0,1.0,TTIME,OUTPUT,L+1,0,0,0,0)
* -  DRAW DASHED VERTICAL LINES--BRANCH IF NO DASHED LINES TO BE DRAWN
* -  MULT IS THE INCREMENT OF THE INDEX OF DEPTH AND IS
* -  USED IN WRITING THE DEPTH ABOVE THE DASHED LINES.
* -
       IF(PTS*LT*1.0)GO TO 100
     MULT=TTIME(L2)/PTS
     JJMAX=IFIX(PTS*AXLEN)
   DO 70 J=1, JJMAX
      ZTIME(J) = 1.0 + FLOAT(J)/PTS
   DO 60 JL=1+30+2
     CALL PLOT(ZTIME(J),YDASH(JL),3)
   CALL PLOT(ZTIME(J)*YDASH(JL+1),2)
  60   CONTINUE
  70   CONTINUE
* -
* -  WRITE DEPTHS ABOVE DASHED LINES
* -
   DO 80 J=1, JJMAX
      1=J*MULT
     IF(DEPTH(I),EQ.*8888,0)GO TO 90
     CALL NUMBER(ZTIME(J),4,7,0,14,DEPTH(I),90,0,-1)
  80   CONTINUE
* -
* -  WRITE CENTERED LABEL (DLABEL) ABOVE PLOT
* -
   CNTR=AXLEN/2.0-1.0
   CALL SYMBOL(CNTR,4,7,0,14,DLABEL,0,0,20)
* -
* -  WRITE CENTERED TITLE ABOVE AXIS LABEL
* -
   CNTR=CNTR-1.2
   GO TO 110
  100  CNTR=AXLEN/2.0-2.2
      CALL SYMBOL(CNTR,5,1,0,30,20HSYNTHETIC SEISMOGRAM,0,0,20)
   CALL PLOT(50,1,1,3)
   CALL CLOSEPF
   RETURN
* ------------------------------------------
* ------------------------------------------
 200  FORMAT(* AMPLITUDE *)
 201  FORMAT(* TIME IN MILLISECONDS *)
 202  FORMAT(* DEPTH IN FEET *)
 203  FORMAT(*AMPLITUDE *)
END
SUBROUTINE SYMSCL(ARRAY,SCLLEN,AXLEN,NPTS)
* -
* SUBROUTINE TAKES THE LARGER OF THE ABSOLUTE VALUES OF FMIN OR FMAX
* -  AND MAKES THE TWO SYMMETRIC ABOUT ZERO. IT THEN DOES THE NORMAL
* -  SCALING OPERATIONS. ARRAY IS THE NAME OF THE ARRAY TO BE SCALED,
* -  SCLLEN IS THE ACTUAL SIZE OF THE PLOT DESIRED, AXLEN IS THE LENGTH
* -  OF THE AXIS (DOES NOT HAVE TO BE SAME AS SCLLEN), AND NPTS IS THE
* -  NUMBER OF DATA POINTS IN ARRAY.
* -
   DIMENSION ARRAY(1)
* -
   FIND REAL MAX AND MIN
* -
      MAX=IFIX(AMMAX(ARRAY,NPTS))
      MIN=IFIX(AMMIN(ARRAY,NPTS))
*-- MAKE MAX AND MIN SYMMETRIC
*--
10 IF(MAX-MIN)10,30,20
   MAX= -MIN
   GO TO 30
20 MIN = -MAX
*--
*-- COMPUTE FACTOR
*--
30 ARRAY(NPTS+2)=FLOAT(2*MAX)/SCLEN
*--
*-- CALCULATE ADJUSTED FMIN
*--
   ARRAY(NPTS+1)=FLOAT(MIN)*AXLEN/SCLEN
*--
*-- CALCULATE DELTA
*--
   ARRAY(NPTS+3)=ABS(FLOAT(MIN))*2.0/SCLEN
RETURN
END
FUNCTION AMMAX(ARRAY,N)
*--
*-- FUNCTION RETURNS MAXIMUM VALUE CONTAINED WITHIN ARRAY
*--
   DIMENSION ARRAY(N)
   AMMAX=ARRAY(1)
   IF(N.EQ.0)RETURN
   DO 10 I=2,N
      IF(ARRAY(I).GT.*AMMAX)AMMAX=ARRAY(I)
   10 CONTINUE
RETURN
END
FUNCTION AMMIN(ARRAY,N)
*--
*-- FUNCTION RETURNS MINIMUM VALUE CONTAINED WITHIN ARRAY
*--
   DIMENSION ARRAY(N)
   AMMIN=ARRAY(1)
   IF(N.EQ.1)RETURN
   DO 10 I=2,N
      IF(ARRAY(I).LT.*AMMIN)AMMIN=ARRAY(I)
   10 CONTINUE
RETURN
END
Appendix 2. Generalized Flow Chart of Program SYNSEIS

Appendix 2 summarizes the main calling program and four subroutines. Eight Calcomp subroutines are also used: IDENT, LIMIT, SCALE, AXIS, SYMBOL, LINE, PLOT, and CLOSEPF.
calculate one-way time

has two-way time increased by one?

yes

no

compute and print average velocity

update total time test (xintg)

end of CVL?

yes

no

calculate final part of seismogram

plots input wave and seismogram on line printer

plot input wave, CVL, and seismogram on plotter

STOP
Appendix 3. Input Cards for Test Case

Card 1.  80-column identification card. Information from this card is printed as a heading for the input wave on both line printer and Calcomp plot.

Cards 2-89.  Input wave amplitudes at 1-millisecond intervals with Format (II, F4.0). Col. 1 is an identification code (=1). Cols. 2-5 are the plus or minus amplitude. Final card amplitude has a flag of 999. Maximum number of amplitudes permitted is 200.

Card 90.  80-column identification card. Information from this card is printed as a heading for the line-printer output and beneath the Calcomp plot of the transit times (CVL).

Card 91.  Parameter card. Col. 1 is an identification code (=2). Cols. 2-5 are initial depth of CVL. Cols. 6-9 are initial transit time in microseconds per foot. Cols. 10-13 are digitizing interval of depths on CVL (for example, 2 feet). If a regular spaced interval is used, depths used need not be entered on succeeding cards. If depths are to be read from input cards, a zero is placed in cols. 10-13. Cols. 14-15 are the number of time lines per inch to be drawn on the seismogram plot. Format (II, F4.0, F4.1).

Cards 92-3,188.  Depths and transit times from the CVL or velocity model. Transit times in microseconds per foot. Col. 1 is an identification code (=2). Cols. 2-5 are depth (need not be entered if regularly spaced; see discussion for card 91). Cols. 6-9 are transit time. Final time is flagged with a zero. Format (II, F4.0, F4.1). 3,096 cards read in for test case. Maximum number of times permitted is 3,500.
Appendices 4-7. Portions of Test Case Output

The test case consisted of 3,096 transit times obtained from the CVL of the Brown well in central Indiana. The log was digitized at 2-foot intervals from 592 to 6,784 feet. Appendix 4 shows a portion of the line-printer listing of the input data (depth and transit times) and the computed output (average velocity, interval velocity, two-way time, reflection coefficient, and amplitude of seismogram). Appendix 5 is the line-printer plot of the input wave (from Biggs, Blakely, and Rudman, 1960). Appendix 6 shows a portion of the line-printer plot of the synthetic seismogram. The plot includes a listing of the depths and reflection coefficients at each millisecond of two-way travel time. Appendix 7 is the Calcomp plot of the input wave, CVL, and synthetic seismogram.

Appendix 4

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<th>TIME</th>
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<th>VELOC</th>
<th>TIME</th>
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DATA ENDS HERE. THE FOLLOWING AMPLITUDES ORIGINATE FROM THE FINAL REFLECTION COEFFICIENT AND ARE NOT NECESSARILY A VALID PART OF THE SYNTHETIC SEISMOGRAM.

\[-0.255\]
\[-1.229\]
\[-1.753\]
\[-2.736\]
\[-3.580\]
\[-4.960\]
\[-2.087\]
\[-2.872\]
\[-8.235\]
\[-0.049\]
\[-0.029\]
\[-0.121\]
\[-1.136\]
\[-1.070\]
\[-0.034\]
\[-0.000\]
\[-0.000\]
Appendix 5

INPUT WAVE FROM BIGGS, 1960, 70-92 CPS
Appendix 6

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