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FORTRAN Computer Program for Seismic Risk Analysis

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FORTRAN COMPUTER PROGRAM FOR SEISMIC RISK ANALYSIS

By ROBIN K. McGUIRE

Abstract

A program for seismic risk analysis is described which combines generality of application, efficiency and accuracy of operation, and the advantage of small storage requirements. The theoretical basis for the program is first reviewed, and the computational algorithms used to apply this theory are described. The information required for running the program is listed. Published attenuation functions describing the variation with earthquake magnitude and distance of expected values for various ground motion parameters are summarized for reference by the program user. Finally, suggestions for use of the program are made, an example problem is described (along with example problem input and output), and the program is listed.

Introduction

This computer program for seismic risk analysis accomplishes several objectives:

1. It allows specification of source-area geometry in a general and convenient manner, independent of the sites at which seismic risk is to be calculated;
2. It performs risk analysis at different sites sequentially and, hence, incurs no computer storage penalty for mapping problems where a large grid of sites is considered;
3. It allows a very general specification of attenuation functions; and
4. It enables the user to make a simple and intelligent trade off between efficiency and accuracy, if necessary.

For calculation of seismic risk at a site, the analyst needs (1) a description of local and regional seismicity, (2) an attenuation function for the ground-motion-intensity measure of interest, and (3) a means of performing the calculations. The first requirement is somewhat site dependent and involves the synthesis of seismic history, and geologic and tectonic evidence. The second requirement is less site specific; attenuation functions are often assumed to apply on regional scales. (A summary of published attenuation functions is listed in the section on "Summary of published attenuation functions" to aid the user in finding a suitable function or to provide a means to compare a newly proposed attenuation law.) The third requirement above is fulfilled by the present program. It is published in the belief that the major time and effort in seismic risk assessment should go into examination and evaluation of alternate seismicity assumptions and ground-motion-intensity parameters, rather than into merely performing the calculations.

Theoretical background

The theory on which this seismic-risk-analysis program is based has been developed over several years (Cornell, 1968, 1971; Merz and Cornell, 1973). A brief description is given here.

Calculations in this program can be represented in the most basic form by the "total probability theorem":

$$P\left[A\right] = \int\int P\left[A | s \text{ and } r\right] f_S(s)\ f_R(r) ds dr \qquad (1)$$

where P indicates probability, A is the event whose probability is sought, and S and R are continuous, independent random variables which influence A. In words, the probability that A occurs can be calculated by multiplying the conditional probability of A given events s and r, times the (independent) probabilities of s and r, and integrating over all possible values of s and r. In this program, A represents the event that a specific value of ground-motion intensity is exceeded at the site of interest during an earthquake. As discussed below, the term "intensity" is used here in a general sense and can mean Modified Mercalli intensity, peak ground acceleration, spectral velocity, or other parameters. Variables s and r represent earthquake size (magnitude or epicentral Modified Mercalli intensity) and distance from the site of interest. Random size and location of events are accounted for as discussed below.

Under the principal option for which this program was written, the conditional probability of (random) intensity I exceeding value i at the site given s and r is evaluated using the normal distribution; this distribution has been used for a variety of ground-motion-intensity measures by various investigators, for example, Esteva (1970); Donovan (1974), and McGuire (1974). The mean of the (conditional) distribution of intensity is taken as

$$m_I(S,R) = c_1 + c_2S + C_3\ln(R + r_0) \qquad (2)$$

where c_1, c_2, c_3, and r_0 are constants, S is earthquake size, and R is epicentral or hypocentral distance. The majority of analytical attenuation functions reported in the section on "Summary of published attenuation functions" are of this form or can be converted to this form by logarithmic transformation (see below). As will be seen, the program calculates integrations over distance numerically; hence the form of the distance term in the above equation is not critical. By means of slight modifications the program can easily handle mean-intensity functions of the form

$$m_I(S,R) = c_1 + c_2S + c_3\ln(R+r_0) + c_4(R+r_0) \qquad (3)$$

This form has been examined by several investigators, for example, Gupta and Nuttli (1975) and Howell and Schultz (1975). (See section on "Summary of published attenuation functions.")

The standard deviation of intensity σ_I is generally taken to be constant, that is, independent of S and R. Using the normal distribution and equation 2, we have

$$P[A|s \text{ and } r] = P[I > i|s \text{ and } r] = \Phi^* \left(\frac{i - c_1 - c_2 s - c_3 \ln(r + r_0)}{\sigma_I} \right) \quad (4)$$

where Φ^* is the complementary cumulative of the standardized normal distribution.

Peak ground motion and spectral intensity measures

When peak-ground-motion values (acceleration, velocity, or displacement) or spectral velocity are used as ground-motion-intensity measures, these variables are generally assumed to be lognormally distributed. Thus, the logarithms of these variables are normally distributed. The mean of, for example, peak ground acceleration A_g as a function of Richter-magnitude M and hypocentral-distance R is often reported as

$$m_{A_g}(M,R) = c_1' \cdot e^{c_2 M} (R+r_0)^{c_3}. \qquad (5)$$

In this case the intensity I discussed above is obtained as the natural logarithm of A_g, S is equivalent to M, and equation 2 is obtained by a logarithmic transformation of equation 5. Parameter σ_I is now the standard deviation of the logarithm of peak ground acceleration. If (as is usual) c_1, c_2, and c_3 are calculated by least-squares regression on the logarithm of the ground-motion or spectral-velocity measure, c_1' is often reported as simply the anti-logarithm of c_1, in which case c_1 is calculated as the logarithm of c_1'. More rigorously, from the relationship between the mean and variance of a normally-distributed variable, and the mean of the corresponding lognormally-distributed variable, c_1' can be estimated as

$$c_1' = \exp(c_1 + \tfrac{1}{2}\sigma_I^2) \tag{6}$$

from which c_1 can be obtained from c_1' and σ_I. Equation 6 gives a less (but still slightly) biased estimate for c_1' (Goldberger, 1968) than simply taking the anti-logarithm of c_1.

The distribution of magnitude, $f_M(m)$, is considered next. The number n_M of earthquakes having magnitude greater than M occurring in a source area is assumed to conform to the relation (Richter, 1958),

$$\log_{10} n_M = a - bM \tag{7}$$

where a and b are constants characteristic of the source area examined. Constant b describes the relative distribution of small and large-magnitude events; larger values of b imply relatively fewer large shocks, and vice versa. Values for b are relatively constant for different areas, ranging from 0.67 to 1.29 for the continental United States (Evernden, (1970). A value of 0.88 is typical of southern California (Allen and others, 1965).

Assuming that sizes of successive events in the source area are independent, it follows from equation 7 that the cumulative distribution of magnitude for each event is given by

$$F_M(m) = k\left[1 - \exp(-\beta(m-m_0))\right] \quad m_0 \le m \le m_1 \tag{8}$$

where m_0 is a lower-bound magnitude (discussed below), m_1 is the maximum magnitude which can originate from the source area, and constants β and k are given by

$$\left.\begin{aligned} \beta &= b \ln 10 \\ k &= \left[1 - \exp(-\beta(m_1-m_0))\right]^{-1} \end{aligned}\right\} \qquad (9)$$

It follows from equation 8 that the density function on magnitude is given by

$$f_M(m) = \beta k \exp(-\beta(m-m_0)) \qquad m_0 \leq m \leq m_1 \qquad (10)$$

Postponing, for the moment, consideration of the density function on distance in equation 1, we can substitute equations 4 and 10 in 1, equate s to m, and obtain the probability that intensity i is exceeded at the site:

$$P[I>i] = \int_r \int_{m_0}^{m_1} \Phi^*\left(\frac{i-c_1-c_2m-c_3\ln(r+r_0)}{\sigma_I}\right) \beta k \exp(-\beta(m-m_0)) f_R(r)\,dm\,dr \qquad (11)$$

Through algebraic manipulation (Cornell, 1971; Merz and Cornell, 1973), the integration on magnitude in equation 10 may be performed analytically (derivation is given in "Appendix A, Derivation of equation 11"), resulting in

$$P[I>i] = \int_r \Big\{ (1-k)\,\Phi^*(z/\sigma_I) + k\,\Phi^*(z'/\sigma_I) + k(r+r_0)^{\frac{\beta c_3}{c_2}} \exp\left(-\frac{i\beta}{c_2} + \frac{\beta c_1}{c_2} + \beta m_0 + \frac{\beta^2\sigma_I^2}{2c_2^2}\right) \left[\Phi^*\left(\frac{z-\beta\sigma_I^2/c_2}{\sigma_I}\right) - \Phi^*\left(\frac{z'-\beta\sigma_I^2/c_2}{\sigma_I}\right)\right]\Big\} f_R(r)\,dr \qquad (12)$$

where constants z and z' are defined in "Appendix A, Derivation of equation 11." The density function on distance, $f_R(r)$, depends on the spatial relationship between the source and site. As discussed in the next section, the program calculates risk associated with intensity i by evaluating the integral in equation 12 numerically.

Once the risk associated with an intensity-level i at a site has been calculated for the occurrence of one earthquake of arbitrary magnitude and location in a source area, the annual expected number of events from that source area that cause intensity i or greater, is obtained by multiplying the single-event risk by the expected number of events during 1 year. The total expected number of events causing intensity $I \geq i$ at the site is obtained by summing the expected number from each source area. If this total is less than about 0.1, this expected number is also an accurate (and conservative) approximation to the risk associated with that intensity level. (This is true for a wide range of mathematical models which could be used to represent successive earthquake occurrences.) In this program, both expected numbers and risks are output; risks are calculated assuming that earthquakes occur as Poisson arrivals, that is, risk=1-exp(-total expected number).

The lower-bound magnitude, m_0, can be used in one of two ways in the program. First (and most commonly), it can be used as a "loose" lower bound (in the terminology of Cornell, 1974), meaning that it is simply a convenient magnitude used to express the activity rate (rate of occurrence of events greater than or equal to that magnitude). Earthquakes of lesser magnitude are assumed to occur, at a rate consistent with that for magnitudes m_0 and greater (that is, the exponential distribution on magnitude is extrapolated to lower magnitudes, using a corresponding and consistent increase in activity rate). In the program, extrapolation is made to magnitude zero, and risk calculations are performed from magnitude zero to m_1. (The choice of magnitude zero for the lower bound of calculations is not critical.)

The second option in the program for use of m_0 is as a "strict" lower bound (again in the terminology of Cornell, 1974). Risk calculations are made only from magnitude m_0 to m_1. This option is useful, for instance, for modeling a piecewise linear log n_M versus M curve (as described in "Guidelines for program use").

The choice of lower-bound option for each source is controlled by the value input for variable LORS, as described in the section on "Required input."

Modified Mercalli intensity.--Site analysis can be performed using Modified Mercalli intensity (MMI) as the intensity measure. In the program, there is no loss of generality in taking MMI to be a continuous random variable. The user must take care, however, in interpreting discrete MMI data for input as a continuous variable, particularly in defining the lower bound and in reinterpreting intensities (from continuous to discrete values) after risks have been calculated.

The equations presented above apply for use of MMI, except that earthquake size is designated by epicentral MMI, I_e. Event size may also be designated by the maximum MMI, and the user should be aware that the epicentral MMI of an earthquake is not always the maximum MMI observed. This may result because of such effects as mislocated epicenters, misreported intensities, and propagation path or site geology. For events documented without instrumental data (and thus without an instrumentally determined epicenter) the epicentral MMI is often taken to be the maximum MMI reported. If these data are used to represent earthquake size for the program, the user should be aware of potential inconsistencies arising because, for a given earthquake, the program will compute nonzero probabilities of site intensities which are greater than the maximum intensity defining the event.

Similarly, nonzero probabilities will be calculated for site intensities greater than the maximum intensity allowable in the surrounding source areas.

Using epicentral MMI I_e, the mean site intensity (equation 2) becomes

$$m_I\ (I_e, R) = c_1 + c_2 I_e + c_3 \ln\ (R + r_0) \qquad (13)$$

where R is now epicentral distance and other parameters are as previously defined. Standard deviation σ_I is now that of MMI about its predicted value. The density function on magnitude, equation 10 becomes a density function on epicentral intensity:

$$f_{I_e}(i_e) = \beta k \exp\ (-\beta(i_e - i_0)) \qquad i_0 \le i_e \le i_1 \qquad (14)$$

where the constants β and k are analogous to the previous definitions.

It is possible to perform an analysis for site MMI using Richter magnitude as the measure of earthquake size. An attenuation equation for site MMI as a function of Richter magnitude and distance is reported by Howell and Schultz (1975). Whichever event-size parameter (magnitude or MMI) is used in the right-hand side of the attenuation function must also be used for the earthquake density function (equation 10 or 14).

The previous comments regarding loose and strict lower bounds for sources apply also to MMI. For loose lower bounds, extrapolation is made to MMI equal to zero, using an occurrence rate consistent with that indicated for $i_e = i_o$.

<u>Limits on attenuation equations</u>.--Several options are available in this program to introduce limits on the attenuation equation 2. The first of these is a limiting radius (denoted as variable RONE in the program) inside of which there is no attenuation of motion. Operationally, the program computes mean intensities for distances less than RONE by substituting RONE for R in equation 2. Mean intensities for earthquakes at greater distances than RONE are not affected. This option is often used when MMI is the intensity measure and the user wishes the mean intensity within radius RONE to be constant (and ordinarily equal to the epicentral intensity). Dispersion of intensities within radius RONE is taken to be the same as dispersion outside this radius; this implies that a particular site might experience a higher MMI than that at the epicenter. Such higher than epicentral intensities might represent local soil conditions or propagating (focusing) effects. If the user wishes the standard deviation of intensities within RONE to be different from the standard deviation outside that radius (particularly if he wishes σ_I to be zero), comment cards in subroutines RISK1 and RISK2 indicate the method of modifying the program to achieve this result.

The second option for limiting the mean values calculated by attenuation equation 2 involves describing a maximum mean intensity as a function of magnitude. Operationally, the equation

$$\text{maximum } m_I(S) = AAA+BBB*S \tag{15}$$

(where the symbol * indicates multiplication) is used to calculate a maximum mean intensity for any earthquake size S. Variables AAA and BBB are input by the user. Equation 15 implicitly defines a radius for each earthquake size S inside of which equation 15 yields a constant mean intensity and outside of which equation 2 governs the mean intensity (fig. 1). Equation 15 is most often used when the intensity measure is (the logarithm of) peak ground acceleration, and when the user wishes to specify a lesser dependence of acceleration on magnitude at close distance than at far distances (this may also be done by specifying a set of tabulated attenuation functions, as is explained below). Note that a limiting mean intensity for all earthquake sizes can be designated with equation 15 by specifying AAA as the absolute limit and BBB as zero. (In this case the limiting equation in figure 1 would become a horizontal line.)

The use of limits RONE and equation 15 is best illustrated by showing the effect of these limits on a typical attenuation equation (of the type given by equations 2 or

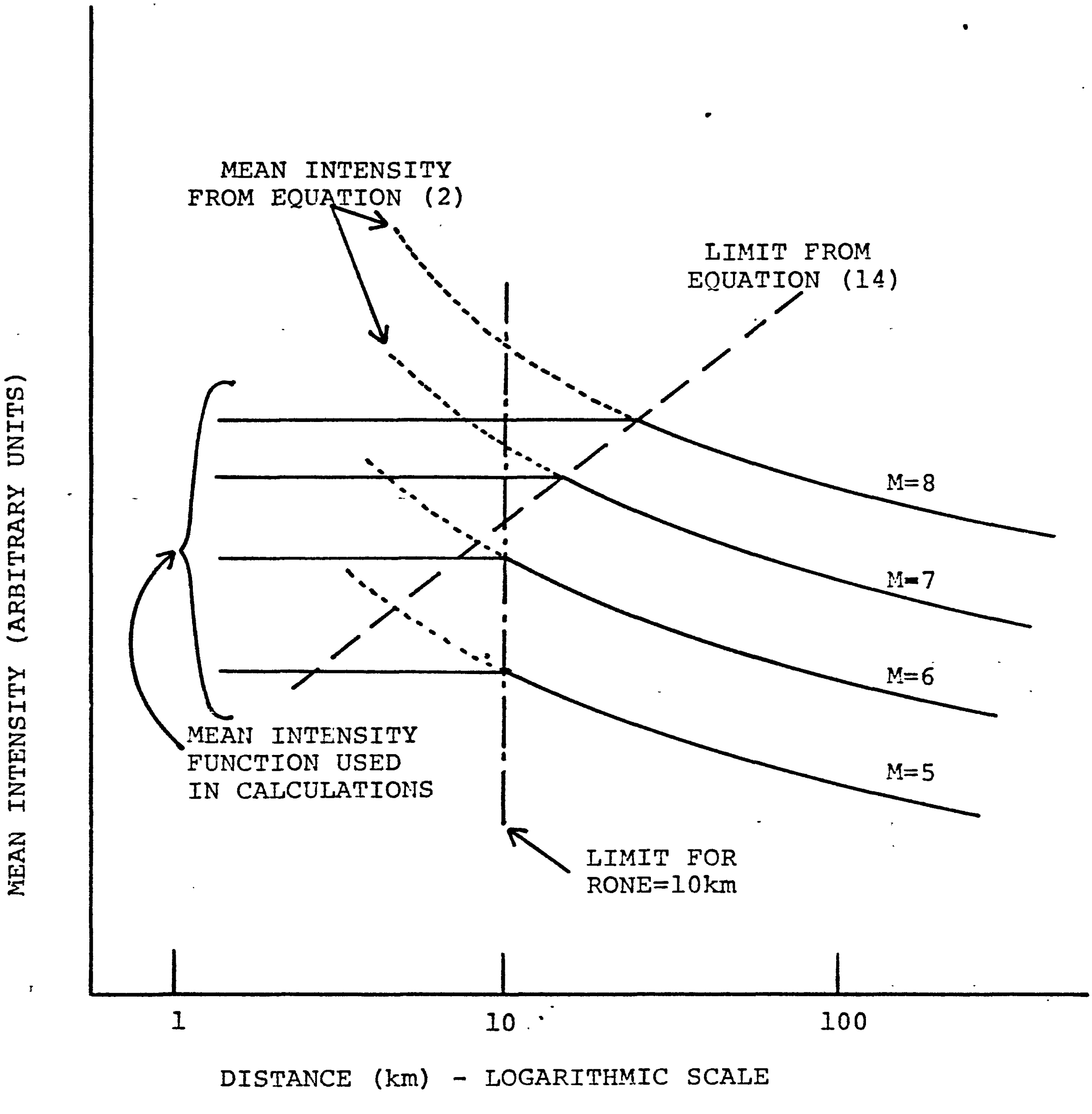

FIGURE 1

EFFECTS OF EQUATION(14) AND PARAMETER RONE
ON MEAN INTENSITY ATTENUATION CURVES

5.) Figure 1 shows mean intensity as a function of distance for earthquakes of several different magnitudes, when both RONE <u>and</u> equation 15 are used as limits on the mean intensity. When both limiting options are used, the lower of the two resulting limit intensities governs.

The form of equation 15 was chosen because it is consistent with the dependence of intensity on magnitude in the attenuation equation 2. Choice of parameters AAA and BBB must be made using judgment and physical arguments because of the dearth of quantitative ground-motion data at small epicentral distances. It is strongly suggested that the user plot his attenuation relationship along with the limiting options used, as in fig. 1, before proceeding with site analysis. The equation of the dashed line in fig. 1 representing limiting equation 15 is

$$m_I = \frac{BBB*c_1 - AAA*c_2}{BBB-c_2} + \frac{BBB*c_3}{BBB-c_2} \ln(R+r_0) \qquad (16)$$

As an alternative to specifying AAA and BBB directly, it may be more convenient for the user to plot his attenuation function for several magnitudes, as in fig. 1, decide on a limiting line such as the dashed line in fig. 1, determine the intercept α and slope γ of this line, and calculate AAA and BBB for program input by the relations:

$$\left.\begin{aligned} AAA &= \alpha + \gamma \frac{(c_2-\alpha)}{\beta-c_3} \\ BBB &= \frac{\gamma c_2}{\beta-c_3} \end{aligned}\right\} \qquad (17)$$

Alternate attenuation functions.--Mean attenuation functions of a form other than equation 2 can easily be handled by this program. Similarly, distributions of intensity residuals other than the normal distribution may be specified. Changes required are that the value of switch JCALC be input as 1 (see the section on "Required input"), and the user's mean-intensity-attenuation function and distribution of residuals be specified in subroutine RISK2 following the comment cards in that subroutine. Under this option a double numerical integration is carried out over magnitude and distance, evaluating equation 1 directly. Program calculations are less efficient than if attenuation equation 2 and a normal distribution of residuals is used, allowing analytical integration over magnitude as described previously. At present (1975) subroutine RISK2 is programed for demonstration purposes to use a mean-intensity-attenuation function identical with equation 2, and a normal distribution of residuals; comment cards indicate the modifications necessary to incorporate changes in the attenuation function and residual distribution.

Program operation

The program evaluates risk for each site-source combination and intensity level by integrating equation 12 numerically, and calculates the total annual expected number of occurrences of intensity greater than those levels of interest at a site by summing the expected numbers from all sources. The total annual risk is calculated assuming that earthquakes occur as Poisson arrivals. To make intelligent choices for such operational parameters as the number of integration steps, and to construct program input for a problem in order to achieve most efficient operation, the program user must understand the operation of the program.

Seismic source areas are specified as a set of arbitrarily shaped quadrilaterals (fig. 2). For ease of input, gross sources may be divided into subsources which are a string of quadrilaterals, each two adjacent subsources having two common corners (the method of source-area specification is described in the following section). A Cartesian coordinate system is used; the location of the origin is arbitrary. The program is easily modified to use a latitude-longitude coordinate system, as explained by comment cards in the main program. Activity rates (yearly number of earthquakes having magnitudes $\geq m_0$) and

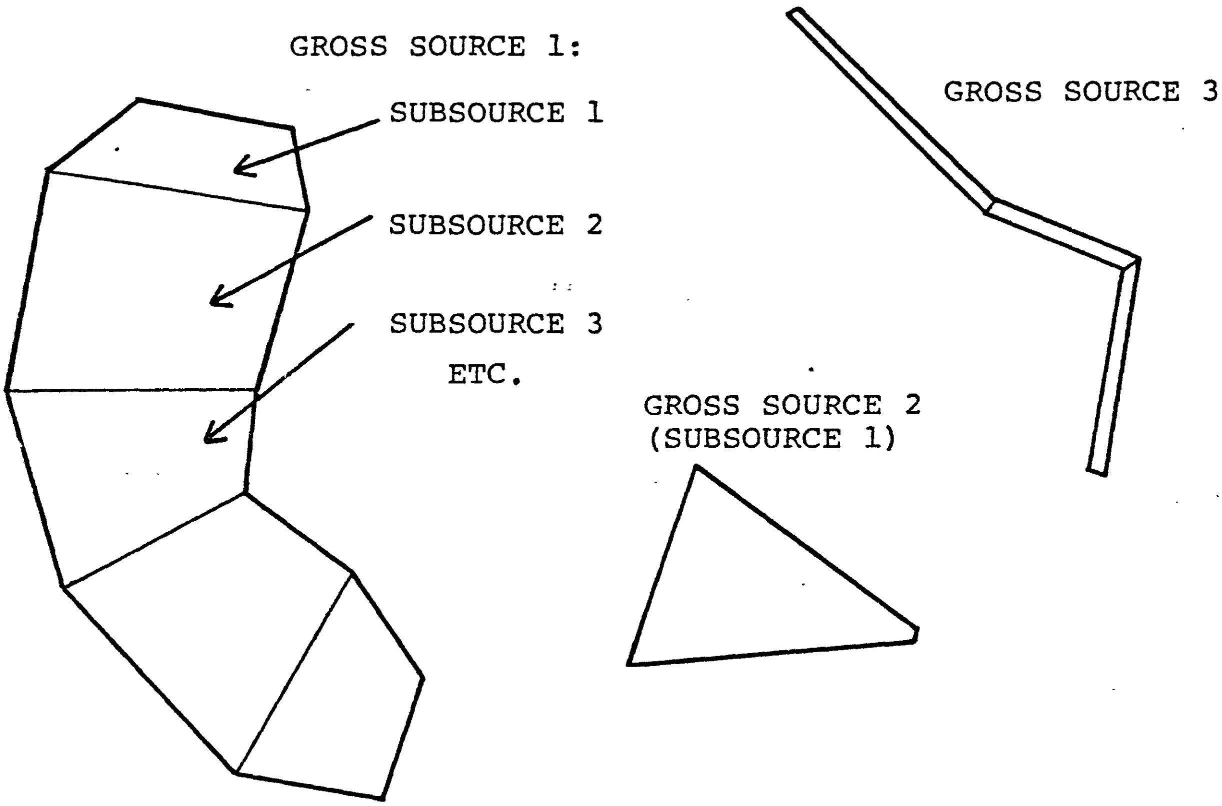

FIGURE 2

TYPICAL SOURCE AREAS

values of β (equation 9) are input for each gross source. The only restrictions on specification of the quadrilaterals are that (1) two sides cannot be colinear, and (2) no reentrant figures (those having a concavity) may be used. A triangular source can be prescribed by using a quadrilateral having one short side (for example, gross-source 2 in fig. 2). Quadrilateral sources, whether in the same or different gross sources, may overlap and may have coincident corners.

Sites to be examined are specified by inputting the (Cartesian) coordinates of each site. As an option, a grid (or grids) of sites may be specified by inputting the X and Y distance between sites in the grid and the number of sites in the X and Y directions (that is, the number of columns and rows in the grid). In this case the coordinates of the first site represent the lower-left corner of the grid. Risks for sites are calculated and are output sequentially in the order specified.

For each site and quadrilateral source, the program computes the closest and farthest distances of the source from the site (fig. 3). The difference between these distances is divided into NSTEP intervals (this parameter being specified in program input), and the distance variable in equation 12 is increased sequentially, starting with the distance from the site to the midpoint of the first interval. For each interval (each distance value) the intersection of

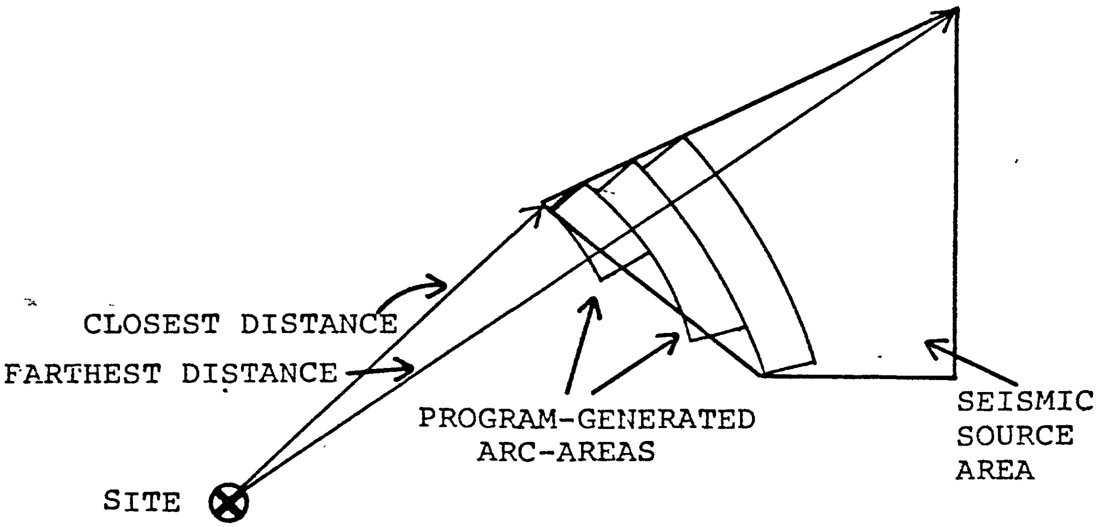

FIGURE 3

ARC AREAS GENERATED BY PROGRAM TO
ASSIGN SEISMICITY WITHIN QUADRILATERAL
SOURCE AREA AS A FUNCTION OF DISTANCE FROM SITE

an arc of constant radius, centered at the site, and the sides of the quadrilateral are computed, and the arc area (the arc length times the interval width) is calculated. Seismicity is assigned to each arc area in the proportion that its area has to that of the entire quadrilateral.

The sum of the arc areas will not exactly equal the area of the quadrilateral because of the approximate method of calculating each arc area (fig. 3). Whenever the difference is more than 5 percent of the true quadrilateral area, a warning message is printed. This situation is generally caused by too few intervals (too small a value for NSTEP), although in some cases increasing NSTEP through a small range will increase the calculated error. Guidelines for choice of values for NSTEP are given in the section on "Guidelines for program use."

Several cases deviate from this basic analysis. When the closest distance from site to quadrilateral source area is between 100 and 250 km, the number of steps used is one-half of NSTEP. When the closest distance is between 250 and 500 km, no numerical integration is done, and all seismic activity is located at the center of the source area (determined by averaging the coordinates of the corner points). Quadrilateral sources farther away than 500 km are not considered in risk computations. These distances can easily be altered to suit the user; see the comment cards referring to this in subroutine OUTSID. For sites located inside quadrilateral source areas, NSTEP circular intervals are considered, from the site to the closest edge (except that the smallest interval width used is 1 km). The number of steps used for the remainder of the source area (outside the largest circle) is a fraction of NSTEP, the fraction determined by the ratio of the remaining area to the total area of the source. The purpose in devising these algorithms to modify NSTEP for particular cases is to promote calculations which trade accuracy for efficiency in situations where such a trade is desirable.

The relative value of NSTEP for sites inside and outside source areas can be changed or can be input separately. Comment cards giving directions for these changes are included in the main program.

For each arc interval, the contribution to the integral of equation 12 is calculated for each intensity of interest. Computation of the arc lengths takes much of the program's operational time for a large problem; hence, changing NSTEP by a factor of 2 will affect a problem's run time by about a factor of 2. Similarly, for a chosen value of NSTEP the run times of different problems are approximately proportional to the number of (quadrilateral) sources times the number of sites in each problem, for the same number of examined intensities. There is no computational advantage to lumping subsources under one gross source; the advantage is in the smaller number of coordinates needed to be input. The run time of any particular problem is proportional to the number of intensities for which risks are calculated.

A coefficient for each gross source must be supplied in the program input. After the expected number of occurrences (of intensity greater than those specified) has been computed for a gross source (and site), this number is multiplied by the (gross) source coefficient before adding to obtain the total expected number (from all gross sources). The normal (most common) value for the coefficient is 1.0; however, fractional values may be used to express subjective probabilities on that source. For instance, duplicate sources, each having a coefficient value of 0.5, may be specified to be identical in all respects except for the assigned activity rate, to indicate uncertainty in this parameter. Alternately, coefficient values of -1.0 may be used to "subtract" one gross source from another. (An example is given in "Guidelines for program use.") Note that the coefficient is applied to the expected number from each source, rather than to the risk from each source.

Parameter values to indicate "background seismicity" may also be input to the program. This is seismicity which cannot be associated with a specific source area.

The activity-rate input is that for a 10,000 km^2 area, and the contribution of background seismicity is calculated for a circle of radius 150 km. This calculation is made once, and the contribution to the expected numbers of occurrences of intensities greater than those in the input list is added to the expected number for each site examined. Note that there is an inconsistency in this procedure, in that the background seismicity is assigned to all areas including source areas having loose lower bounds. Hence, for magnitudes less than the upper-bound-background seismicity magnitude, two specifications of seismicity for loose-lower-bound source areas have been made. For activity rates and upper-bound magnitudes usually associated with background seismicity, the errors will be very small. The errors will be largest for sites near and within loose lower-bound sources that have an upper-bound magnitude and activity rate close to those of the specified background seismicity. To alleviate these errors, the user may wish to specify a gross source identical in geometry to the real gross source but having an activity rate and bounding magnitudes equal to those of the background seismicity and a source coefficient of minus one.

The advantages of the algorithms used in this program over alternatives (Cornell, 1974; Shah and others, 1975) are worth enumerating:

1. Source-area specification is quite general; virtually all possible geometries for source areas may be specified efficiently by the quadrilaterals used here.
2. Source-area specification is independent of the site being investigated; hence, alternate sites may be compared, or grids of sites (for mapping purposes) may be analyzed using one source-area specification.
3. The size of the program is quite small; no storage penalty is incurred by analyzing a grid of sites, as each site is considered and analyzed sequentially. Using a moderate amount of core space, seismic source areas may be specified for a large area (for example, a large section of the United States); sites can then be chosen for later analyses at will.
4. An optimum trade off between accuracy and efficiency is easily approximated through variation of the number of steps used in the numerical integration as a function of site-to-source distance.
5. The program is easily converted to work on a latitude-longitude coordinate system (see comment cards in main program).
6. An optional variation of the program allows use of any form of attenuation function and residual distribution. Even a tabulated attenuation function may be used.

Present limitations on input are as follows:

maximum number of gross sources.........10

maximum number of subsources (in each gross source)................10

maximum number of intensities to be examined........................12

maximum number of risks for which associated intensities are to be calculated..................... 8

number of sites to be examined.........unlimited

These limits can be modified by changing dimension statements as noted in the comment cards of the main program.

Required input

Input required for program operation is described in this section. All input is read in the main program and is echo printed for reference. Because the program does only a minimal amount of data checking, care must be taken in input preparation and review.

Card 1 (Format 20A4): Title

Any 80 characters may be used to describe the problem.

Card 2 (Format 3I10): NSTEP, JCALC, JPRNT.

NSTEP is the number of integration steps used in integrating over distance for each site-source combination. Refer to the discussion of this parameter in the section on "Program operation" and "Guidelines for program use."

JCALC is the flag indicating how integration on magnitude is to be performed:

JCALC=0 is used for analytical integration, and the form of the attenuation function is that described in the section on "Program operation."

JCALC=1 is used for numerical integration on magnitude. The user must supply his attenuation function in subroutine RISK2. Refer to comment cards in that subroutine.

JPRNT is the flag indicating desired output:

JPRNT=0 is used to print only total expected numbers and risks at a site (normally used when a grid of sites is being examined).

JPRNT=1 is used to print expected numbers from each site-source combination (normally used when examining a single site).

Card 3 (Format I5, 12F5.3): NLEI, TI(1), TI(2),...TI(NLEI).

NLEI is the number of intensities to be examined.

TI(1), TI(2), and so on, are intensities for which expected numbers and risks are calculated at each site. Note, as discussed in the section on "Theoretical background," that the values for TI(i) may be Modified Mercalli intensity, or the natural logarithm of ground acceleration, velocity, displacement, or spectral velocity. In printing results, the program prints both TI(i) and its antilogarithm. Values for array TI must be specified in increasing order.

Card 4 (Format 8F10.2): RISKS(1), RISKS(2),...RISKS(8).

RISKS(1), RISKS(2), and so on are risks (probabilities of exceedance) for which the corresponding intensities are desired. These intensities are calculated by interpolation, on a logarithmic scale, between intensities (in the list of examined intensities, TI) having larger and smaller risks. Both the corresponding intensity and its anti-logarithm are printed. Values for array RISKS must be specified in order of decreasing risk. If fewer than eight values are desired, leave succeeding spaces on the card blank. To avoid large errors and subsequent misinterpretation, the program will not extrapolate to calculate intensity values corresponding to risk levels specified; it is the user's obligation to choose values for array TI which will result in risks which bound those specified in array RISKS. This is, of course, a matter of judgment and experience. The user must be cautioned that in a grid site system appropriate values for array TI may vary considerably for the different sites examined. The intensities interpolated for levels specified in RISKS will be most accurate for closely spaced values of TI.

Card 5 (Format 8F10.2): C1, C2, C3, SIG, RZERO, RONE, AAA, BBB.

C1, C2, C3, and RZERO are parameters in the attenuation equation 2 for mean intensity discussed in the section on "Theoretical background":

$$m_I(S,R)=C1+C2*S+C3*ALOG(R+RZERO)$$

SIG is the standard deviation of residuals about the mean. If no dispersion of residuals is desired, insert a very small value for SIG (rather than exactly 0.0).

RONE is the limiting radius inside of which no attenuation of motion is desired, for values of focal distance closer than RONE, the mean intensity is calculated using RONE in place of R in the attenuation equation above. If this feature is not desired, insert zero for RONE.

AAA and BBB are parameters in the equation limiting the mean intensity (see the section on "Program operation"):

$$\max m_I(s)=AAA+BBB*S$$

The value specified for BBB must be between zero and C2 for this limiting equation to make sense. If it is not, an error message will result and program operation will terminate.

Card 6 (Format 24I3): NGS, NRS(1), NRS(2),...NRS(NGS).

NGS is the number of gross sources to be specified.

NRS(1), NRS(2), and so on are the number of subsources in gross source 1, 2, etc. See the section on "Program operation" for a general description of the source specification.

Card (Set) 7 (Format I10, 6F10.2): LORS(I), COEF(I), AMO(I), AM1(I), BETA(I), RATE(I), FDEPTH(I).

There must be NGS+1 of these cards, one for each gross source and one for background seismicity.

LORS(I) is a flag indicating whether the source area has a loose or strict lower bound (see the section on "Program operation"):

LORS(I)=0 implies a loose lower bound.

LORS(I)=1 implies a strict lower bound.

COEF(I) is a coefficient modifying the expected number of exceedances from gross-source I (see the section on "Program operation"). Its most common value is +1.0.

AMO(I) is the loose or strict lower-bound magnitude or intensity for gross-source I.

AM1(I) is the upper-bound magnitude or intensity for gross-source I.

BETA(I) is the value of β for gross-source I. It is equal to the natural logarithm of 10, times the Richter b value for the source (see equation 6).

RATE(I) is the rate of occurrence of events having magnitudes of intensities greater than AMO(I). If a discrete distribution on intensities has been used to calculate the rate, the user may wish to specify AMO(I) as one-half intensity unit lower than the lowest intensity used to establish the rate. Note that for gross sources RATE(I) is in units of number per year; for background seismicity it is in units of number per year per 10,000 km.

FDEPTH(I) is the focal depth of events in gross-source I, in kilometres. If epicentral distances are required for all sources and for background seismicity for the attenuation function, insert zero for FDEPTH(I).

If no background seismicity is desired, leave the last card in this set completely blank.

Card (Set) 8 (Format 4F10.2): X1, Y1, X2, Y2.

There must be NRS(1)+NRS(2)+...+NRS(NGS)+NGS of these cards. The first NRS(1)+1 cards specify coordinates of subsources for gross-source 1, the next NRS(2)+1 cards specify coordinates of subsources for gross-source 2, and so on. Internally, the point X1, Y1 is connected to point X2, Y2, as well as to both the previous and subsequent points designated as X1, Y1, as long as these are both in the same gross source. Point X2, Y2 is connected similarly. An example is elucidating. The following points, for two gross sources having two subsources each, designate the source areas of fig. 4:

0.0	0.0	10.0	0.0
0.0	5.0	10.0	8.0
-5.0	10.0	6.0	15.0
10.0	20.0	11.0	20.0
15.0	15.0	16.0	15.0
15.0	0.0	16.0	0.0

Card (Set) 9 (Format 2I5, 4F10.2): NX, NY, XZERO, YZERO, XDELTA, YDELTA.

There can be any number of these cards, one for each site or grid of sites to be examined.

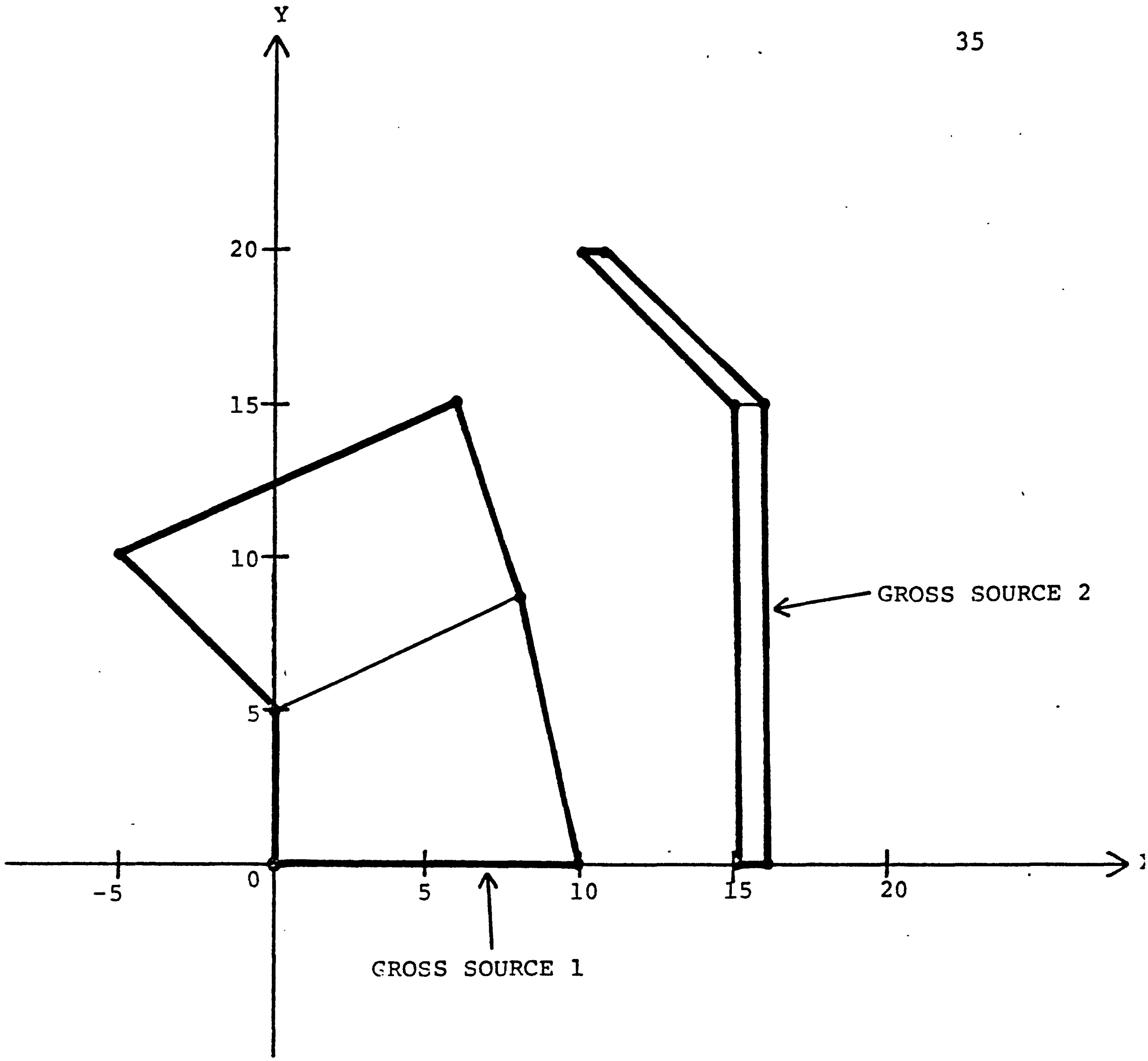

FIGURE 4

SOURCE AREAS SPECIFIED IN EXAMPLE

NX and NY are the number of grid points in the X (east-west) and Y (north-south) directions; that is, they are the number of columns and rows in the grid of sites to be examined. For specification of a single site, NX and NY must have values of unit. Zero or negative values for NX or NY are meaningless and will cause program termination.

XZERO and YZERO are the coordinates of the site to be examined, or are the lower left corner of the grid if NX and/or NY are greater than one.

XDELTA and YDELTA are the grid spacings in the X and Y directions. When the grid option is not used, these variables may be left blank or set equal to zero.

Final Card:

Insert one blank card at the end of the input deck.

Summary of published attenuation functions

Table 1 lists some published attenuation functions and the data on which they are based. Not included in this summary are functions derived primarily from events on continents other than North America, and functions derived from observations of underground nuclear explosions. Refer to Ambrayses (1974) for a summary of attenuation functions derived from observations on other continents; refer to Environmental Research Corporation (1974) for a summary of attenuation functions derived from nuclear explosions.

Particular care should be taken when using reported attenuation functions describing Modified Mercalli intensity. For the distance variable in these functions some investigators use epicentral or hypocentral distance to sites where intensities were reported, whereas others use distance to an equivalent circular isoseismal. The two methods are not equivalent, but comparisons are often made in the literature, ignoring the difference.

Table 1.--Summary of published attenuation functions

Reference	Data source	Distance parameter	Dependent variable	Equation	Standard Deviation
Blume (1966)	Southern California	Epicentral distance Δ (mi)	Peak ground acceleration a_g (g)	$a_g = \frac{a_o}{1+(\Delta/h)^2}$ where a_o is epicentral acceleration, h is focal depth	Not reported
Brazee (1972)	United States east of long. 106°W	Epicentral distance Δ (mi)	Distance over which a Modified Mercalli intensity is felt	$\text{Log } \Delta = a_I + b_I I_e$ where I_e is epicentral intensity, a_I and b_I are tabulated	Not reported
Cloud and Perez (1971)	North and South America	Epicentral distance or distance to fault Δ (mi)	Maximum single component ground acceleration a_g (g)	$a_g = 3.0-2 \log(\Delta+43)$ $a_g = 3.5-2 \log(\Delta+80)$	Not reported
Cornell and Merz (1974)	Northeastern United States, rock sites	Epicentral distance Δ (mi)	Modified Mercalli intensity	$I = 2.6+I_e-1.3 \ln \Delta$ $\Delta \geq 10$ mi	$\sigma_I = 0.2$
	Northwestern United States, all sites	--------do---------	-------do--------	$I = 3.1+I_e-1.3 \ln \Delta$ $\Delta \geq 10$ mi where I_e is epicentral intensity	$\sigma_I = 0.5$
Donovan (1974)	San Fernando, rock sites	Distance to energy center R (km)	Peak ground acceleration a_g (gals)	$a_g = 12.783 \times 10^6 (R+25)^{-2.77}$	Not reported
	San Fernando, soil sites	--------do--------	------do------	$a_g = 2.054 \times 10^5 (R+25)^{-1.83}$	Not reported
	San Fernando, all sites	--------do--------	------do------	$a_g = 5.165 \times 10^5 (R+25)^{-2.04}$	$\sigma_{\ln a_g} = 0.481$
	------do-----	--------do--------	------do------	$a_g = 1.84 \times 10^4 R^{-1.42}$	Not reported
	Western North America, Japan, Papua-New Guinea	--------do--------	------do------	$a_g = 1080 e^{-0.5M} (R+25)^{-1.32}$	$\sigma_{\ln a_g} = 0.707$
Donovan (1973)	Worldwide	Hypocentral distance, epicentral distance, or distance to fault R (km)	Peak ground acceleration a_g (gals)	$a_g = 1320 e^{0.58M} (R+25)^{-1.52}$	$\sigma_{\ln a_g} = 0.84$
Duke and others (1972)	San Fernando, all sites	Distance to energy center R (km)	Peak ground acceleration a_g (g)	$a_g = \frac{6.69}{R} e^{-0.0097R}$	$\sigma_{a_g} = 0.052$ g
	------do-----	--------do--------	Spectral acceleration s_g (g)	$s_g = \frac{5.34}{R} e^{-0.0068R}$	$\sigma_{s_g} = 0.053$ g
Esteva (1970)	See reference	Hypocentral distance R (km)	Peak ground acceleration a_g (gals)	$a_g = 1230 e^{0.8M} (R+25)^{-2}$	$\sigma_{\ln a_g} = 1.2$
	------do-----	--------do--------	Peak ground velocity v_g (cm/sec)	$v_g = 15 e^M (R+0.17 e^{0.59M})^{-1.7}$	$\sigma_{\ln v_g} = 0.84$
Esteva and Rosenblueth (1964)	West Coast of United States	Hypocentral distance R (km)	Peak ground acceleration a_g (gals)	$a_g = 2000 e^{0.8M} R^{-2}$	See reference
	-------do------	-------do--------	Peak ground velocity v_g (cm/sec)	$v_g = 20 e^M R^{-1.7}$	See reference
Esteva and Villaverde (1974)	Western United States	Hypocentrel distance R (km)	Peak ground acceleration a_g (gals)	$a_g = 5600 e^{0.8M} (R+40)^{-2}$	$\sigma_{\ln a_g} = 0.64$
	------do------	------do---------	Peak ground velocity v_g (cm/sec)	$v_g = 32 e^M (R+25)^{-1.7}$	$\sigma_{\ln v_g} = 0.74$

Table 1.--Summary of published attenuation functions--Continued

Reference	Data source	Distance parameter	Dependent variable	Equation	Standard Deviation
Esteva and Villaverde (1974)	Western United States	Hypocentral distance R (km)	Maximum average spectral acceleration $\bar{A}$ (gals)	$\bar{A}=69600\ e^{0.8M}(R+70)^{-2}$	$\sigma_{\ln \bar{A}}=0.75$
	------do------	------do---------	Maximum average spectral velocity $\bar{V}$ (cm/sec)	$\bar{V}=250\ e^{M}(R+60)^{-1.7}$	$\sigma_{\ln \bar{V}}=0.64$
Gupta and Nuttli (1975)	Central United States	Epicentral distance to isoseismal Δ (km)	Modified Mercalli intensity	$I=I_e+3.7-0.0011\ \Delta$ $-2.7\ \log\ \Delta$ where I_e is epicentral intensity	Not reported
Gutenberg and Richter (1956)	California	Epicentral distance	Peak ground acceleration	Graphical	Not reported
Housner (1965)	Western United States, and Central and South America	Distance to fault	Peak ground acceleration	Graphical	Not reported
Howell and Schultz (1975)	California coast	Epicentral distance to isoseismal Δ (km)	Modified Mercalli intensity	$I=I_e+0.874-0.422\ \ln\ \Delta$ $-0.0186\ \Delta$	$\sigma_I=0.64$
	----do----	----------do----------	Logarithm of Modified Mercalli intensity	$\ln\ I=\ln\ I_e+0.16-0.0763\ \ln\ \Delta$ $-0.0023\ \Delta$	$\sigma_I=0.44$
	Rocky Mountains, Washington, Oregon	Epicentral distance to isoseismal Δ (km)	Modified Mercalli intensity	$I=I_e+1.802-0.628\ \ln\ \Delta$ $-0.009\ \Delta$	$\sigma_I=0.61$
	------do-------	----------do----------	Logarithm of Modified Mercalli intensity	$\ln\ I=\ln\ I_e+0.322-0.1098\ \ln\ \Delta$ $-0.0012\ \Delta$	$\sigma_I=0.47$
	Central and Eastern United States and Canada	Epicentral distance to isoseismal Δ (km)	Modified Mercalli intensity	$I=I_e+3.278-0.989\ \ln\ \Delta$ $-0.0029\ \Delta$	$\sigma_I=0.64$
	------do-------	----------do----------	Logarithm of Modified Mercalli intensity (Other forms of equations examined and reported also)	$\ln\ I=\ln\ I_e+0.480-0.139\ \ln\ \Delta$ $-0.00075\ \Delta$ where I_e is epicentral intensity	$\sigma_I=0.43$
McGuire (1974)	West Coast of United States	Hypocentral distance R (km)	Peak ground acceleration a_g (gals)	$a_g=472\text{x}10^{0.28M}(R+25)^{-1.3}$	$\sigma_{\log\ a_g}=0.222$
	------do-------	---------do---------	Peak ground velocity v_g (cm/sec)	$v_g=5.64\text{x}10^{0.40M}(R+25)^{-1.2}$	$\sigma_{\log\ v_g}=0.273$
	------do-------	---------do---------	Peak ground displacement d_g (cm)	$d_g=0.393\text{x}10^{0.43M}(R+25)^{-0.88}$	$\sigma_{\log\ d_g}=0.330$
	------do-------	---------do---------	Spectral velocity (T=1 sec, ζ=0.02) s (in/sec) (Spectral attenuation equations given for other periods and dampings also.)	$s=0.428\text{x}10^{0.38M}(R+25)^{-0.59}$	$\sigma_{\log\ s}=0.274$
Mickey (1971)	See reference	Hypocentral distance, R (km)	Peak particle acceleration a (g)	$a=3.04\text{x}/0^{0.74m-4}R^{-1.4}$	See reference
	-----do------	------do------	Peak particle velocity v (cm/sec)	$v=4.06\text{x}10^{0.88m-3}R^{-1.5}$	-----do------
	-----do------	------do------	Peak particle displacement d (cm)	$d=5.66\text{x}10^{1.1m-5}R^{-1.2}$ where m is body-wave magnitude	-----do------

Table 1.--Summary of published attenuation functions--Continued

Reference	Data source	Distance parameter	Dependent variable	Equation	Standard Deviation
Milne and Davenport (1969)	Western United States, Central America, Chile	Epicentral distance Δ (km)	Peak ground acceleration a_g (g)	$a_g = \frac{0.69\ e^{1.64M}}{1.1\ e^{1.1M} + \Delta^2}$	Not reported
	Eaatern Canada	-------do----------	Modified Mercalli intensity	$I=I_7-9.66-0.0037\ \Delta +1.38\ M+0.00528\ \Delta\ M$ where I_7 is site intensity of M=7 event at diatance Δ	$\sigma_I=0.53$
Neumann (1954)	West Coaat of United States	Epicentral distance Δ (mi)	Modified Mercalli intensity	$I=I_e+0.15-3.17\ \log R$ $R\geq 1.12$ miles where I_e is epicentral intensity	Not reported
Nuttli (1973a)	Central United States	Epicentral distance	Vertical particle acceleration, velocity, and displacement at 3 frequencies for Rayleigh waves	Graphical and tabular for various earthquakes	Not reported
Nuttli (1973b)	Central United States	Epicentral distance	Suatained ground acceleration, velocity, and displacement at 3 frequencies for surface waves	Graphical and tabular	Not reported
Orphal and Lahoud (1974)	California	Hypocentral distance R (km)	Peak ground acceleration a_g (g)	$a_g=0.066\times10^{0.4M}R^{-1.39}$	See reference
	California and nuclear exploaions	-------do--------	Peak ground velocity v_g (cm/sec)	$v_g=0.726\times10^{0.52M}R^{-1.34}$	-----do------
	------do------	-------do--------	Peak ground displacement d_g (cm)	$d_g=0.0471\times10^{0.57M}R^{-1.18}$	-----do------
Rasmussen and others (1974)	Puget Sound, Washington	Epicentral distance	Modified Mercalli intensity	Graphical; data and limits given for each earthquake	Not calculated; data shown
Schnabel and Seed (1973)	Western United States	Diatance to fault	Peak ground acceleration	Graphical	Not reported
Stepp (1971)	Puget Sound, Washington	Hypocentral distance to isoseismal R (km)	Modified Mercalli intensity	$I=I_e-2.017\ \log(R/h) -0.008(R/h)$ where I_e is epicentral intensity, h is focal depth	Not reported

Guidelines for program use

In this section, suggestions are given for most efficient and accurate use of this program. In general, more insight is gained for a particular problem by spending effort and computer time calculating approximate and relative risks associated with a range of input assumptions, rather than by calculating highly accurate risks for a single set of assumptions.

Number of integration steps.--The effect of the number of integration steps on efficiency was discussed in the section on "Program operation." To illustrate the degree of accuracy associated with various levels of efficiency, two sites affected by a square seismic-source area were examined, as shown in fig. 5.

Using a typical attenuation function for peak ground acceleration and an occurrence rate of once per year, the annual risks associated with various acceleration levels were computed for sites A and B, using various values for NSTEP (the input variable describing the number of integration steps). The largest value examined was 25, representing the most accurate calculation. For acceleration levels corresponding to about 15 percent annual risk at the two sites, the variation in calculated risk as a

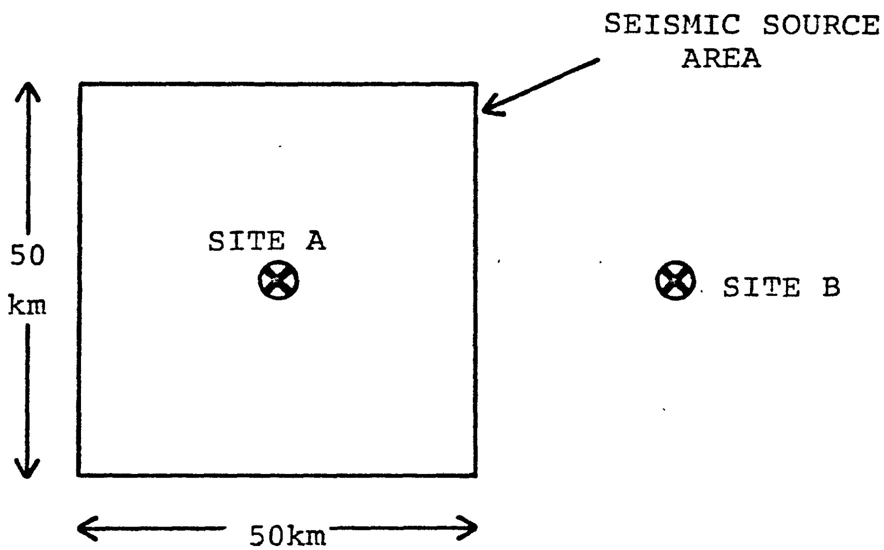

FIGURE 5

SITES AND SOURCE AREA USED
FOR INTEGRATION ACCURACY STUDY

function of the number of integration steps was determined and is shown in fig. 6. In this illustration a relative error of +1 percent in risk level from the 15 percent annual risk implies an estimated annual risk of 15.15 percent. The lowest detectable error, corresponding to a change in the last significant digit, is ±0.6 percent.

As evident in fig. 6, the inaccuracy resulting from fewer integration steps is small, on the order of several percent, for NSTEP values as small as 5 or 10. This conclusion holds for smaller risk levels as well (for example, an annual risk of 0.001). Hence, a value of 10 will not induce great inaccuracies, and is suggested for most problems. Refer also to the discussion on modeling faults as source areas later in this section.

The erratic behavior of relative error in estimated risk with NSTEP for site B results from erratic (but small) errors in the estimated source size as discussed in the section on "Program operation."

<u>Use of source-area coefficient</u>.--The source-area coefficient (variable COEF in the program) is useful for expressing subjective probabilities, as discussed previously in the section on "Program operation." Also, by use of some care and cunning, it can be used to gain efficiency without loss of accuracy.

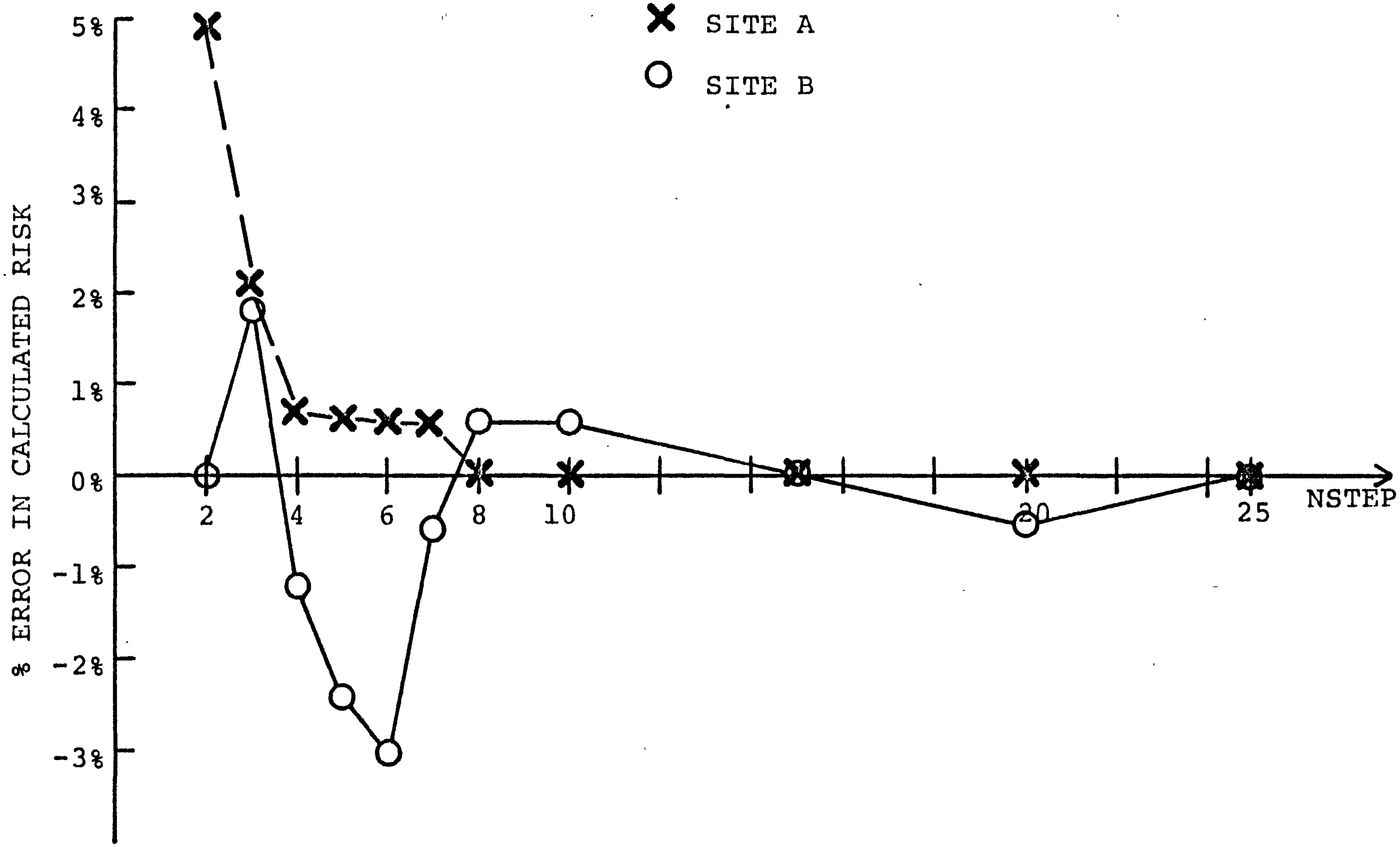

FIGURE 6

PERCENT ERROR IN RISK LEVEL AS
FUNCTION OF NUMBER OF INTEGRATION STEPS

As an extreme example, consider the (perhaps unrealistic) source area shown in fig. 7. This might be represented in program input by four quadrilateral sources defined as rectangles.

Alternately, the source could be designated by one gross source representing the perimeter rectangle and a separate gross source (having coefficient equal to minus one) representing the interior rectangle. In effect, the program would subtract the expected number of exceedances due to the second gross source from the number due to the first, to arrive at the expected number from the "real" source as shown in fig. 7. The rates of occurrence of events for the two gross sources must be correctly calculated before input so that the difference is the rate of occurrence for the real source.

Because run time of the program for large problems is directly related to the number of quadrilateral sources, the run time associated with this simple example would be decreased by about a factor of two if the suggested method of input were adopted. Similar efficiencies may be gained by altering seismicities of sections of large source areas by negative strict-lower-bound sources, rather than by defining many small sources, each only for areas having homogeneous seismicity. For small problems (such as analysis

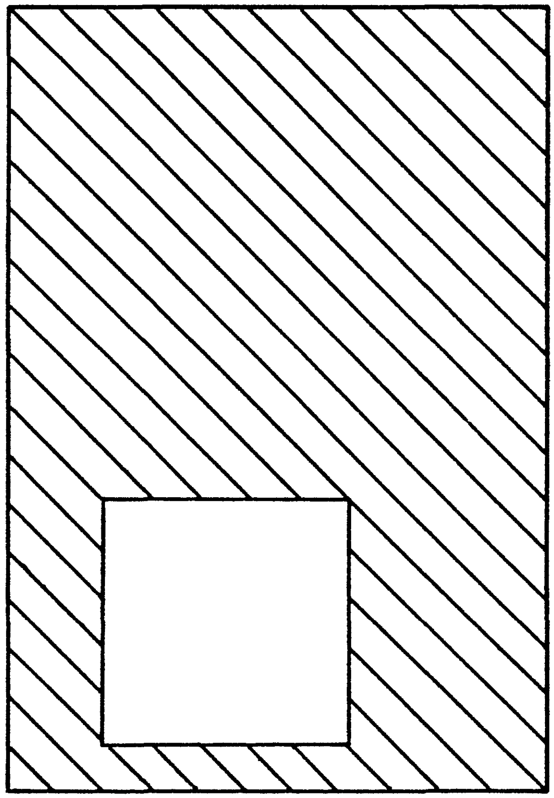

FIGURE 7

HYPOTHETICAL SOURCE AREA

(SHOWN SHADED)

of a single site) the difference in efficiency between two representations of a source area will be slight; in this case ease of input should govern the selection.

<u>"Piecewise linear" frequency-magnitude relations.</u>--
The use of truncated exponential distributions on magnitude is abundant in the seismic-risk literature. With the option of defining sources having strict lower bounds, it is tempting to try to fit two or more truncated exponential distributions to nonlinear cumulative histograms of magnitudes (or epicentral intensities) observed for a hypothesized source area and plotted on logarithmic paper.

The problem is that the complementary cumulative distribution function of a truncated exponential distribution does not plot linearly on logarithmic paper, and the complementary cumulative of two truncated exponential distributions is not continuous. Figure 8 shows the plotted complementary cumulative of a magnitude distribution modeled as two truncated exponentials. In fact, choosing a magnitude distribution and estimating parameters for it is tricky; as thoroughly discussed by Cornell, (1974). Whatever method is used, the data should be compared graphically with calculated points from the chosen distribution, to illustrate the degree to which the chosen distribution models observations.

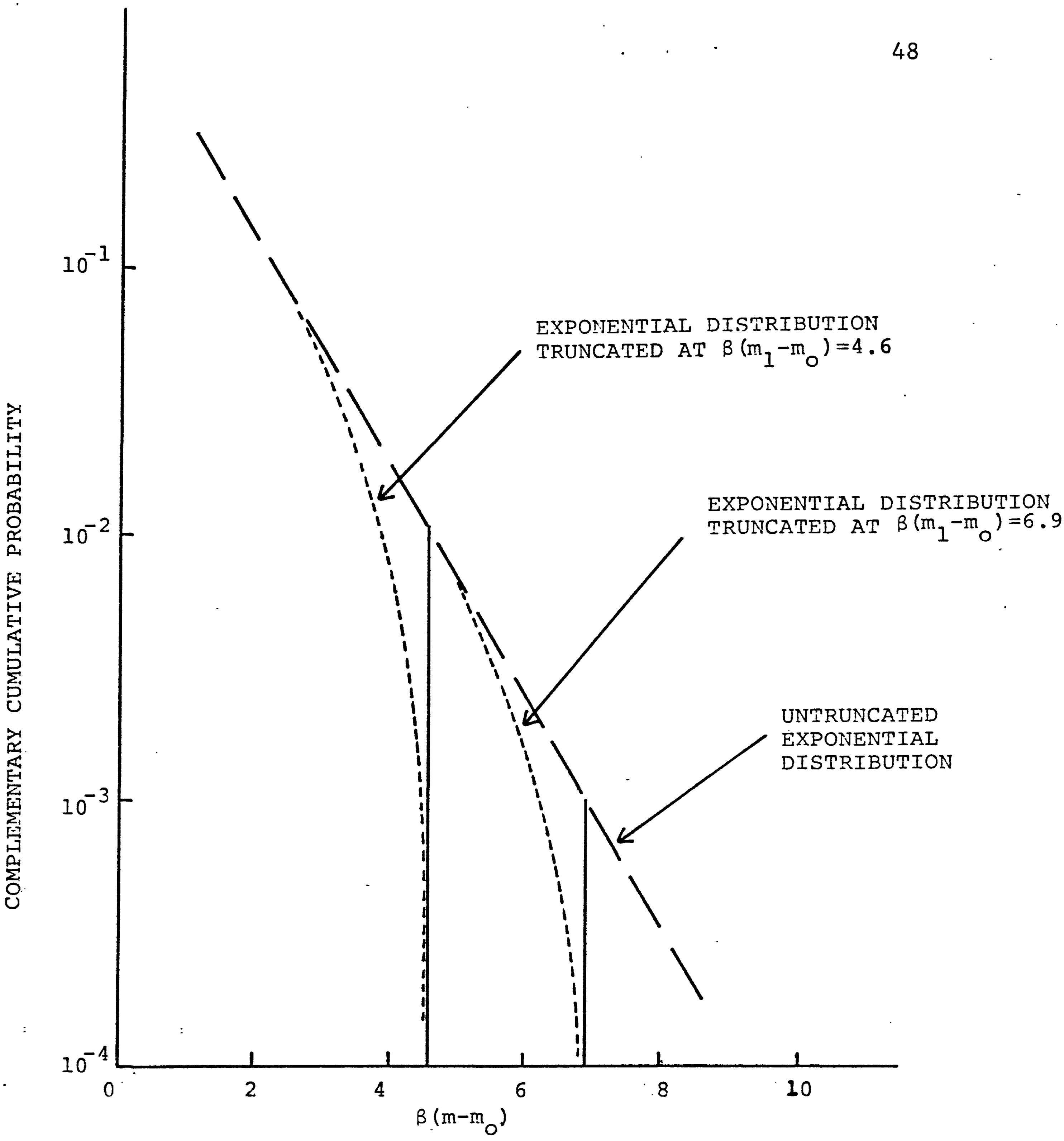

FIGURE 8

COMPLEMENTARY CUMULATIVE OF
TRUNCATED EXPONENTIAL DISTRIBUTIONS
(AFTER CORNELL, 1974)

Modeling faults.--Faults may easily be modeled using this program by specifying them as narrow source areas.

For a site 16 km (closest hypocentral distance) from a fault 100 km long, using an attenuation function describing peak ground acceleration, comparison was made between this program and a separate, very accurate (and inefficient) program that integrates over line sources directly. This comparison showed the following:

1. The trade off between accuracy and efficiency is not circumvented by performing the numerical integration of a fault modeled as a line source.
2. For a value of NSTEP equal to 10, the inaccuracy at all levels of intensity (and risk) is about 9 percent in the estimated risk for the fault modeled as an area 0.1 km wide. As expected, the error decreases as distance increases from the source. Hence, this level of inaccuracy for many problems represents a limit on the expectable error, at least for acceleration. This results because (a) most sites will be greater than 16 km from the nearest fault, particularly when non-zero focal depths of events are specified, (b) limits on the attenuation function, that is, variable RONE and equation 14, may erase the effect of distance (and, hence, errors resulting from the method in which

seismicity is assigned as a function of distance) for sites within 16 km of the source, and (c) faults may, in fact, be more accurately modeled by thin sources rather than by lines.

3. The inaccuracy is reduced by increasing the number of integration steps. Using NSTEP=25 decreased errors in estimated risks to 2-3 percent. Interestingly, increasing the width of the source area used to model the fault decreases the error; a source area 2 km wide, using NSTEP=10, results in errors of 2-3 percent in estimated risks.

The tolerable level of inaccuracy ultimately depends on the user. Especially in cases where fault locations are not well known, it may be acceptable to use source areas of 1-2 km wide, using NSTEP=10. For highly accurate risk calculations at sites close to well-located faults, the user should consider very narrow source areas and larger values to NSTEP. This can be achieved easily and efficiently by specifying a large value for NSTEP and modifying the radii in subroutine OUTSID at which NSTEP is decreased (see comment cards in subroutine OUTSID). For sites at 40 km or more hypocentral distance from the modeled fault, errors in estimated risk, using a narrow source area (0.1 km wide) and NSTEP=10, are generally 1 percent or less.

Use of annual risks.--The calculation of risks for any time period from the annual risks output by this program is simple. Assuming the risks in successive years are independent, the risk R_N for a lifetime of N years is obtained from the annual risk R_A by the equation

$$R_N = 1-(1-R_A)^N$$

which can be inverted to calculate the annual risk corresponding to a risk R_N in N years.

Alternately, the activity rates specified for the source areas may be the number of events in N years, in which case the program outputs risks for N years corresponding to the intensities specified and assumes that the risks input (for which intensities are desired) are for N years.

Example problem

Input and output from an example problem demonstrating use of the program is given in the section on "Example problem input and output." The source areas used are shown in fig. 9, and parameter values describing these source areas are listed in table 2. The intensity parameter is peak ground acceleration (in gals), and values for the attenuation equation parameters are listed in table 3.

Gross-source 1 represents a general source area within which seismic events are not associated with a well-defined tectonic structure. Gross-source 2 represents a fault zone 1 km wide. Gross-source 3, having a source coefficient of -1, is used to represent an area which is considered aseismic; hence, this "negative" source is used to negate the background seismicity observed elsewhere in the region and specified as background seismicity in the program input.

C.P.U. time for this particular problem is approximately 14 seconds on a DEC-10 computer. Doubling the value of NSTEP (to 20) increases the run time to 26 seconds. Halving the list of examined intensities (to four) and specifying NSTEP=10 decreases the run time to 8 seconds.

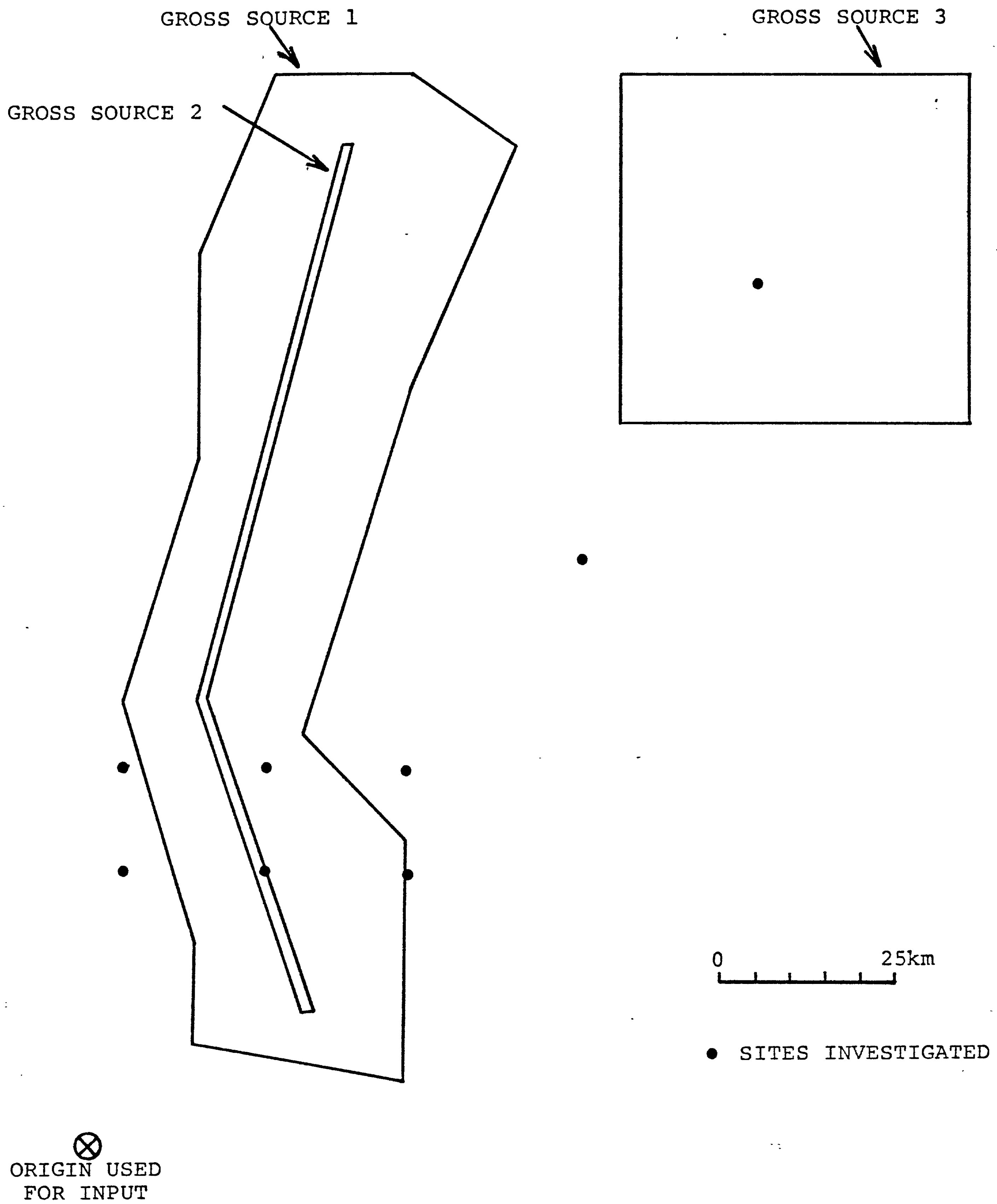

FIGURE 9

SOURCE AREAS AND SITES
IN EXAMPLE PROBLEM

Table 2.--Source-area parameter values in example.

	LORS(i)	COEF(i)	AMO(i)	AM1(i)	BETA(i)	RATE(i)	FDEPTH(i)
Gross source:							
1---------	0	1.0	5.0	6.0	2.03	0.05	10.0
2---------	0	1.0	5.0	7.5	2.03	0.10	10.0
3---------	0	-1.0	4.0	5.0	2.03	0.10	10.0
Background	0	1.0	4.0	5.0	2.03	0.40	10.0

Table 3.--Attenuation-function parameter values in example.

Function							
C1	C2	C3	SIG	RZERO	RONE	AAA	BBB
6.16	0.645	-1.3	0.511	25.0	0.0	100000.0	0.0

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Appendix A, Derivation of equation 11

An observation of I is given by

$$I = c_1 + c_2M + c_3 \ln R' + \varepsilon \tag{18}$$

where $R' = R + r_0$ and ε is a normally distributed variable with mean zero and standard derivation σ_I. The cumulative distribution for magnitude is given by equation 7:

$$F_m(m) = k\left[1 - \exp(-\beta(m - m_0))\right] \quad m_0 \leq m \leq m_1 \tag{19}$$

where constants have been previously defined. Equation 10, written in the following form:

$$P[I > i] = \int_r \int_{m_0}^{m_1} P\left[\varepsilon > \frac{i - M_I}{\sigma_I} \,\middle|\, m, r\right] f_m(m) f_R(r)\, dm\, dr \tag{20}$$

can be rewritten as:

$$P[I > i] = \int_r \int_{-\infty}^{+\infty} P\left[M > c_2(i - c_1 - c_3 \ln R' - \varepsilon) \,\middle|\, \varepsilon, r\right] f_\varepsilon(\varepsilon) f_R(r)\, d\varepsilon\, dr \tag{21}$$

For a given value of i there are two important values of ε, defined by the upper and lower magnitudes:

$$\begin{aligned} z &= i - c_1 - c_2 m_1 - c_3 \ln R' \\ z' &= i - c_1 - c_2 m_0 - c_3 \ln R' \end{aligned} \tag{22}$$

These two values define three ranges for ε :

1. $-\infty < \varepsilon < z$, in which case

$$P[M > c_2(i - c_1 - c_3 \ln R' - \varepsilon | \varepsilon, r)] = 0$$

2. $z < \varepsilon < z'$, in which case

$P[M > c_2 \mid i - c_1 - c_3 \ln R' - \varepsilon|\varepsilon, r]$ can be evaluated by (the complement of) equation 19

3. $z < \varepsilon < \infty$, in which case

$P[M > c_2(i - c_1 - c_3 \ln R' - \varepsilon|\varepsilon, r)] = 1$

Substituting these and the normal density function on ε into equation 21 gives

$$P[I > i] = \int_r \{ \int_z^{z'} (1 - k + k \exp(-\beta(m^* - m_0))) \frac{1}{\sigma^2 \sqrt{2\pi}} e^{\frac{-\varepsilon^2}{2\sigma^2}} d\varepsilon + \Phi^*(z'/\sigma) \} f_R(r) dr \qquad (23)$$

where

$$m^* = c_2 (i = c_1 - c_3 \ln R' - \varepsilon) \qquad (24)$$

and Φ^* is the complementary cumulative of the standardized normal distribution. Substituting 24 into 23 and using the substitution $\zeta = \varepsilon - \frac{\beta \sigma_I^2}{c_2}$, the integral on ε in equation 23 can be transformed into the form of an integral on the standardized normal distribution, yielding the result

$$P[I > i] = \int_r \{ (1-k) \Phi^* (z/\sigma) + k \Phi^* (z'/\sigma) + k (R')^{\frac{\beta c_3}{c_2}} \exp \left(- \frac{i\beta}{c_2} + \frac{\beta c_1}{c_2} + \beta m_0 + \frac{\beta^2 \sigma_I^2}{2c_2^2}\right) \left[\Phi^* \left(\frac{z - \beta\sigma_I^2/c_2}{\sigma_I}\right) - \Phi^* \left(\frac{z' - \beta\sigma_I^2/c_2}{\sigma_I}\right)\right] \} f_R(r) dr \qquad (25)$$

APPENDIX B

EXAMPLE PROBLEM INPUT AND OUTPUT

```
EXAMPLE PROBLEM OF SEISMIC RISK ANALYSIS FOR PEAK GROUND ACCELERATION.
        10         0         1
    8 3.91 4.61 5.01 5.30 5.52 5.70 5.99 6.21
 0.1       0.02      0.01      0.005
 6.16      0.645     -1.30     0.511     25.       0.0       100000.  0.
  3   5   2  1
          0 1.0      5.0       6.0       2.03      .05       10.
          0 1.0      5.0       7.5       2.03      0.10      10.
          0 -1.0     4.0       5.0       2.03      0.1       10.
          0 1.0      4.0       5.0       2.03      0.4       10.
 15.       15.       45.       10.
 15.       30.       45.       45.
  5.       65.       30.       60.
 15.       100.      45.       110.
 15.       130.      60.       145.
 25.       155.      45.       155.
 30.       20.       31.       20.
 15.       65.       16.       65.
 35.       145.      36.       145.
 75.       105.      125.      105.
 75.       155.      125.      155.
    3    2  5.0       40.       20.       15.
    1    1  70.       85.
    1    1  95.       125.
```

```
         EXAMPLE PROBLEM OF SEISMIC RISK ANALYSIS FOR PEAK GROUND ACCELERATION.

NSTEP =    10 JCALC =      0 JPRNT =      1

LIST OF EXAMINED INTENSITIES      3.91     4.61     5.01     5.30     5.52     5.70     5.99     6.21

RISKS DESIRED   0.1000  0.0200  0.0100  0.0050  0.0000  0.0000  0.0000  0.0000

ATTENUATION DATA:    C1       C2       C3     SIGMA   RZERO     RONE      AAA      BBB
                   6.16     0.65    -1.30     0.51   25.00     0.00********     0.00

NO. OF GROSS SOURCES      3
NO. OF SUBSOURCES IN GROSS SOURCES      5    2    1

GROSS SOURCE    L/S      COEF        M0         M1       BETA     RATE/YR   FDEPTH
       1         0       1.00       5.00       6.00     2.0300    0.0500   10.0000
       2         0       1.00       5.00       7.50     2.0300    0.1000   10.0000
       3         0      -1.00       4.00       5.00     2.0300    0.1000   10.0000
(BACKGROUND)     0       1.00       4.00       5.00     2.0300    0.4000   10.0000

GROSS SOURCE  1 SUBSOURCE COORDINATE DATA      15.00     15.00     45.00     10.00
GROSS SOURCE  1 SUBSOURCE COORDINATE DATA      15.00     30.00     45.00     45.00
GROSS SOURCE  1 SUBSOURCE COORDINATE DATA       5.00     65.00     30.00     60.00
GROSS SOURCE  1 SUBSOURCE COORDINATE DATA      15.00    100.00     45.00    110.00
GROSS SOURCE  1 SUBSOURCE COORDINATE DATA      15.00    130.00     60.00    145.00
GROSS SOURCE  1 SUBSOURCE COORDINATE DATA      25.00    155.00     45.00    155.00

GROSS SOURCE  2 SUBSOURCE COORDINATE DATA      30.00     20.00     31.00     20.00
GROSS SOURCE  2 SUBSOURCE COORDINATE DATA      15.00     65.00     16.00     65.00
GROSS SOURCE  2 SUBSOURCE COORDINATE DATA      35.00    145.00     36.00    145.00

GROSS SOURCE  3 SUBSOURCE COORDINATE DATA      75.00    105.00    125.00    105.00
GROSS SOURCE  3 SUBSOURCE COORDINATE DATA      75.00    155.00    125.00    155.00

GROSS SOURCE  1 SUBSOURCE   1 EXACT AREA     750.0
GROSS SOURCE  1 SUBSOURCE   2 EXACT AREA     750.0
GROSS SOURCE  1 SUBSOURCE   3 EXACT AREA    1137.5
GROSS SOURCE  1 SUBSOURCE   4 EXACT AREA    1125.0
GROSS SOURCE  1 SUBSOURCE   5 EXACT AREA     587.5
GROSS SOURCE  1               TOTAL AREA    4350.0

GROSS SOURCE  2 SUBSOURCE   1 EXACT AREA      45.0
GROSS SOURCE  2 SUBSOURCE   2 EXACT AREA      80.0
GROSS SOURCE  2               TOTAL AREA     125.0

GROSS SOURCE  3 SUBSOURCE   1 EXACT AREA    2500.0
GROSS SOURCE  3               TOTAL AREA    2500.0

RESULTS FOR BACKGROUND SEISMICITY
            INTENSITY:      3.91     4.61     5.01     5.30     5.52     5.70     5.99     6.21
   ANTILOG(INTENSITY):     49.90   100.48   149.90   200.34   249.64   298.87   399.41   497.70
(BACKGROUND) E(NO/YR):   .469E+00 .331E-01 .572E-02 .136E-02 .411E-03 .142E-03 .216E-04 .446E-05
```

RESULTS FOR SITE LOCATION 5.00 40.00

INTENSITY:	3.91	4.61	5.01	5.30	5.52	5.70	5.99	6.21
ANTILOG(INTENSITY):	49.90	100.48	149.90	200.34	249.64	298.87	399.41	497.70
SOURCE 1 1 E(NO/YR):	.756E-01	.749E-02	.173E-02	.524E-03	.192E-03	.787E-04	.159E-04	.410E-05
SOURCE 1 2 E(NO/YR):	.157E+00	.163E-01	.409E-02	.136E-02	.547E-03	.243E-03	.573E-04	.168E-04
SOURCE 1 3 E(NO/YR):	.479E-01	.434E-02	.896E-03	.244E-03	.812E-04	.305E-04	.529E-05	.120E-05
SOURCE 1 4 E(NO/YR):	.597E-02	.330E-03	.410E-04	.704E-05	.158E-05	.419E-06	.399E-07	.562E-08
SOURCE 1 5 E(NO/YR):	.118E-02	.451E-04	.412E-05	.544E-06	.984E-07	.216E-07	.151E-08	.166E-09
CAUTION: NUMERICAL INTEGRATION ERROR IN AREA IS 9.25 % FOR (OUTSIDE) SOURCE 2 1								
SOURCE 2 1 E(NO/YR):	.504E+00	.554E-01	.156E-01	.612E-02	.297E-02	.161E-02	.570E-03	.243E-03
SOURCE 2 2 E(NO/YR):	.121E+00	.130E-01	.349E-02	.129E-02	.578E-03	.290E-03	.870E-04	.318E-04
SOURCE 3 1 E(NO/YR):	-.356E-03	-.345E-05	-.126E-06	-.831E-08	-.885E-09	-.131E-09	-.695E-11	-.267E-12
(BACKGROUND) E(NO/YR):	.469E+00	.331E-01	.572E-02	.136E-02	.411E-03	.142E-03	.216E-04	.446E-05
ALL SOURCES E(NO/YR):	.138E+01	.130E+00	.315E-01	.109E-01	.478E-02	.239E-02	.757E-03	.301E-03
ALL SOURCES RISK:	.749E+00	.122E+00	.311E-01	.109E-01	.477E-02	.239E-02	.757E-03	.301E-03

RISKS:	0.100000	0.020000	0.010000	0.005000
INTENSITY:	4.67	5.13	5.32	5.51
ANTILOG(INTENSITY):	106.49	169.24	204.76	246.45

RESULTS FOR SITE LOCATION 25.00 40.00

INTENSITY:	3.91	4.61	5.01	5.30	5.52	5.70	5.99	6.21
ANTILOG(INTENSITY):	49.90	100.48	149.90	200.34	249.64	298.87	399.41	497.70
SOURCE 1 1 E(NO/YR):	.190E+00	.200E-01	.507E-02	.172E-02	.702E-03	.317E-03	.771E-04	.231E-04
SOURCE 1 2 E(NO/YR):	.280E+00	.299E-01	.782E-02	.275E-02	.116E-02	.546E-03	.142E-03	.449E-04
SOURCE 1 3 E(NO/YR):	.590E-01	.549E-02	.117E-02	.329E-03	.113E-03	.436E-04	.798E-05	.190E-05
SOURCE 1 4 E(NO/YR):	.705E-02	.407E-03	.525E-04	.926E-05	.212E-05	.573E-06	.562E-07	.807E-08
SOURCE 1 5 E(NO/YR):	.135E-02	.538E-04	.507E-05	.685E-06	.126E-06	.282E-07	.200E-08	.223E-09
SOURCE 2 1 E(NO/YR):	.112E+01	.123E+00	.348E-01	.138E-01	.681E-02	.378E-02	.142E-02	.647E-03
SOURCE 2 2 E(NO/YR):	.133E+00	.144E-01	.388E-02	.144E-02	.649E-03	.327E-03	.989E-04	.365E-04
SOURCE 3 1 E(NO/YR):	-.715E-03	-.908E-05	-.397E-06	-.301E-07	-.353E-08	-.533E-09	-.242E-10	-.301E-11
(BACKGROUND) E(NO/YR):	.469E+00	.331E-01	.572E-02	.136E-02	.411E-03	.142E-03	.216E-04	.446E-05
ALL SOURCES E(NO/YR):	.225E+01	.226E+00	.585E-01	.214E-01	.985E-02	.515E-02	.177E-02	.758E-03
ALL SOURCES RISK:	.895E+00	.203E+00	.568E-01	.212E-01	.980E-02	.514E-02	.176E-02	.758E-03

RISKS:	0.100000	0.020000	0.010000	0.005000
INTENSITY:	4.83	5.32	5.51	5.71
ANTILOG(INTENSITY):	125.46	203.68	248.20	301.12

RESULTS FOR SITE LOCATION 45.00 40.00

INTENSITY:	3.91	4.61	5.01	5.30	5.52	5.70	5.99	6.21
ANTILOG(INTENSITY):	49.90	100.48	149.90	200.34	249.64	298.87	399.41	497.70
SOURCE 1 1 E(NO/YR):	.174E+00	.182E-01	.462E-02	.157E-02	.644E-03	.293E-03	.727E-04	.223E-04
SOURCE 1 2 E(NO/YR):	.134E+00	.138E-01	.343E-02	.113E-02	.452E-03	.201E-03	.474E-04	.140E-04
SOURCE 1 3 E(NO/YR):	.403E-01	.352E-02	.693E-03	.179E-03	.570E-04	.205E-04	.332E-05	.715E-06
SOURCE 1 4 E(NO/YR):	.673E-02	.380E-03	.478E-04	.823E-05	.185E-05	.489E-06	.464E-07	.648E-08
SOURCE 1 5 E(NO/YR):	.134E-02	.529E-04	.494E-05	.663E-06	.121E-06	.269E-07	.189E-08	.208E-09

CAUTION: NUMERICAL INTEGRATION ERROR IN AREA IS 15.94 % FOR (OUTSIDE) SOURCE 2 1

SOURCE 2 1 E(NO/YR):	.415E+00	.456E-01	.128E-01	.501E-02	.241E-02	.130E-02	.453E-03	.190E-03
SOURCE 2 2 E(NO/YR):	.895E-01	.956E-02	.252E-02	.899E-03	.390E-03	.188E-03	.516E-04	.174E-04
SOURCE 3 1 E(NO/YR):	-.132E-02	-.213E-04	-.109E-05	-.933E-07	-.121E-07	-.202E-08	-.972E-10	-.122E-10
(BACKGROUND) E(NO/YR):	.469E+00	.331E-01	.572E-02	.136E-02	.411E-03	.142E-03	.216E-04	.446E-05
ALL SOURCES E(NO/YR):	.133E+01	.124E+00	.298E-01	.102E-01	.437E-02	.215E-02	.650E-03	.249E-03
ALL SOURCES RISK:	.735E+00	.117E+00	.294E-01	.101E-01	.436E-02	.214E-02	.650E-03	.249E-03

RISKS:	0.100000	0.020000	0.010000	0.005000
INTENSITY:	4.66	5.11	5.30	5.48
ANTILOG(INTENSITY):	105.13	166.43	200.91	240.85

RESULTS FOR SITE LOCATION 5.00 55.00

INTENSITY:	3.91	4.61	5.01	5.30	5.52	5.70	5.99	6.21
ANTILOG(INTENSITY):	49.90	100.48	149.90	200.34	249.64	298.87	399.41	497.70
SOURCE 1 1 E(NO/YR):	.393E-01	.362E-02	.749E-03	.202E-03	.667E-04	.246E-04	.414E-05	.914E-06
SOURCE 1 2 E(NO/YR):	.183E+00	.192E-01	.488E-02	.166E-02	.682E-03	.310E-03	.766E-04	.234E-04
SOURCE 1 3 E(NO/YR):	.114E+00	.114E-01	.269E-02	.842E-03	.320E-03	.136E-03	.297E-04	.818E-05
SOURCE 1 4 E(NO/YR):	.115E-01	.769E-03	.115E-03	.230E-04	.588E-05	.175E-05	.202E-06	.333E-07
SOURCE 1 5 E(NO/YR):	.210E-02	.992E-04	.107E-04	.162E-05	.326E-06	.788E-07	.641E-08	.793E-09
SOURCE 2 1 E(NO/YR):	.528E+00	.581E-01	.163E-01	.644E-02	.313E-02	.171E-02	.612E-03	.266E-03
SOURCE 2 2 E(NO/YR):	.285E+00	.311E-01	.860E-02	.330E-02	.156E-02	.825E-03	.278E-03	.114E-03
SOURCE 3 1 E(NO/YR):	-.585E-03	-.687E-05	-.285E-06	-.207E-07	-.234E-08	-.367E-09	-.161E-10	-.205E-11
(BACKGROUND) E(NO/YR):	.469E+00	.331E-01	.572E-02	.136E-02	.411E-03	.142E-03	.216E-04	.446E-05
ALL SOURCES E(NO/YR):	.163E+01	.157E+00	.391E-01	.138E-01	.617E-02	.315E-02	.102E-02	.417E-03
ALL SOURCES RISK:	.804E+00	.146E+00	.384E-01	.137E-01	.615E-02	.314E-02	.102E-02	.417E-03

RISKS:	0.100000	0.020000	0.010000	0.005000
INTENSITY:	4.72	5.19	5.39	5.58
ANTILOG(INTENSITY):	112.47	180.17	218.55	263.90

RESULTS FOR SITE LOCATION 25.00 55.00

INTENSITY:	3.91	4.61	5.01	5.30	5.52	5.70	5.99	6.21
ANTILOG(INTENSITY):	49.90	100.48	149.90	200.34	249.64	298.87	399.41	497.70
SOURCE 1 1 E(NO/YR):	.748E-01	.739E-02	.170E-02	.512E-03	.187E-03	.758E-04	.151E-04	.382E-05
SOURCE 1 2 E(NO/YR):	.293E+00	.313E-01	.820E-02	.289E-02	.123E-02	.576E-03	.150E-03	.476E-04
SOURCE 1 3 E(NO/YR):	.161E+00	.164E-01	.401E-02	.131E-02	.517E-03	.228E-03	.530E-04	.154E-04
SOURCE 1 4 E(NO/YR):	.142E-01	.100E-02	.156E-03	.324E-04	.852E-05	.259E-05	.311E-06	.525E-07
SOURCE 1 5 E(NO/YR):	.247E-02	.123E-03	.137E-04	.213E-05	.440E-06	.108E-06	.904E-08	.114E-08
SOURCE 2 1 E(NO/YR):	.903E+00	.996E-01	.281E-01	.112E-01	.548E-02	.303E-02	.113E-02	.509E-03
SOURCE 2 2 E(NO/YR):	.335E+00	.367E-01	.102E-01	.393E-02	.187E-02	.992E-03	.339E-03	.140E-03
SOURCE 3 1 E(NO/YR):	-.128E-02	-.206E-04	-.106E-05	-.903E-07	-.117E-07	-.195E-08	-.947E-10	-.107E-10
(BACKGROUND) E(NO/YR):	.469E+00	.331E-01	.572E-02	.136E-02	.411E-03	.142E-03	.216E-04	.446E-05
ALL SOURCES E(NO/YR):	.225E+01	.226E+00	.581E-01	.212E-01	.969E-02	.504E-02	.170E-02	.720E-03
ALL SOURCES RISK:	.895E+00	.202E+00	.564E-01	.210E-01	.965E-02	.503E-02	.170E-02	.720E-03

RISKS:	0.100000	0.020000	0.010000	0.005000
INTENSITY:	4.83	5.31	5.51	5.70
ANTILOG(INTENSITY):	125.27	203.03	247.10	299.38

RESULTS FOR SITE LOCATION 45.00 55.00

INTENSITY:	3.91	4.61	5.01	5.30	5.52	5.70	5.99	6.21
ANTILOG(INTENSITY):	49.90	100.48	149.90	200.34	249.64	298.87	399.41	497.70
SOURCE 1 1 E(NO/YR):	.721E-01	.713E-02	.165E-02	.504E-03	.187E-03	.777E-04	.162E-04	.433E-05
SOURCE 1 2 E(NO/YR):	.134E+00	.138E-01	.342E-02	.113E-02	.447E-03	.198E-03	.460E-04	.134E-04
SOURCE 1 3 E(NO/YR):	.841E-01	.810E-02	.180E-02	.528E-03	.188E-03	.750E-04	.145E-04	.363E-05
SOURCE 1 4 E(NO/YR):	.134E-01	.921E-03	.139E-03	.280E-04	.718E-05	.213E-05	.244E-06	.397E-07
SOURCE 1 5 E(NO/YR):	.244E-02	.119E-03	.132E-04	.203E-05	.415E-06	.101E-06	.831E-08	.103E-08
CAUTION: NUMERICAL INTEGRATION ERROR IN AREA IS 7.93 % FOR (OUTSIDE) SOURCE 2 1								
SOURCE 2 1 E(NO/YR):	.313E+00	.344E-01	.960E-02	.373E-02	.178E-02	.947E-03	.319E-03	.129E-03
SOURCE 2 2 E(NO/YR):	.162E+00	.175E-01	.474E-02	.176E-02	.796E-03	.400E-03	.120E-03	.439E-04
SOURCE 3 1 E(NO/YR):	-.261E-02	-.556E-04	-.347E-05	-.346E-06	-.508E-07	-.941E-08	-.484E-09	-.467E-10
(BACKGROUND) E(NO/YR):	.469E+00	.331E-01	.572E-02	.136E-02	.411E-03	.142E-03	.216E-04	.446E-05
ALL SOURCES E(NO/YR):	.125E+01	.115E+00	.271E-01	.904E-02	.382E-02	.184E-02	.538E-03	.199E-03
ALL SOURCES RISK:	.713E+00	.109E+00	.267E-01	.900E-02	.381E-02	.184E-02	.538E-03	.199E-03

RISKS:	0.100000	0.020000	0.010000	0.005000
INTENSITY:	4.63	5.09	5.27	5.45
ANTILOG(INTENSITY):	102.89	161.94	194.80	232.85

RESULTS FOR SITE LOCATION 70.00 85.00

INTENSITY:	3.91	4.61	5.01	5.30	5.52	5.70	5.99	6.21
ANTILOG(INTENSITY):	49.90	100.48	149.90	200.34	249.64	298.87	399.41	497.70
SOURCE 1 1 E(NO/YR):	.800E-02	.536E-03	.791E-04	.157E-04	.396E-05	.116E-05	.132E-06	.213E-07
SOURCE 1 2 E(NO/YR):	.134E-01	.101E-02	.167E-03	.364E-04	.995E-05	.312E-05	.393E-06	.688E-07
SOURCE 1 3 E(NO/YR):	.430E-01	.377E-02	.740E-03	.190E-03	.597E-04	.212E-04	.333E-05	.695E-06
SOURCE 1 4 E(NO/YR):	.287E-01	.234E-02	.421E-03	.993E-04	.290E-04	.966E-05	.135E-05	.258E-06
SOURCE 1 5 E(NO/YR):	.618E-02	.405E-03	.578E-04	.110E-04	.268E-05	.759E-06	.803E-07	.122E-07
CAUTION: NUMERICAL INTEGRATION ERROR IN AREA IS 14.68 % FOR (OUTSIDE) SOURCE 2 1								
SOURCE 2 1 E(NO/YR):	.424E-01	.449E-02	.116E-02	.397E-03	.164E-03	.748E-04	.183E-04	.551E-05
CAUTION: NUMERICAL INTEGRATION ERROR IN AREA IS 7.20 % FOR (OUTSIDE) SOURCE 2 2								
SOURCE 2 2 E(NO/YR):	.124E+00	.133E-01	.354E-02	.127E-02	.552E-03	.265E-03	.715E-04	.235E-04
SOURCE 3 1 E(NO/YR):	-.278E-01	-.147E-02	-.186E-03	-.330E-04	-.772E-05	-.213E-05	-.221E-06	-.336E-07
(BACKGROUND) E(NO/YR):	.469E+00	.331E-01	.572E-02	.136E-02	.411E-03	.142E-03	.216E-04	.446E-05
ALL SOURCES E(NO/YR):	.707E+00	.575E-01	.117E-01	.335E-02	.122E-02	.515E-03	.117E-03	.345E-04
ALL SOURCES RISK:	.507E+00	.559E-01	.116E-01	.335E-02	.122E-02	.515E-03	.117E-03	.345E-04

RISKS:	0.100000	0.020000	0.010000	0.005000
INTENSITY:	4.43	4.87	5.05	5.21
ANTILOG(INTENSITY):	83.52	130.54	155.25	182.44

RESULTS FOR SITE LOCATION 95.00 125.00

INTENSITY:	3.91	4.61	5.01	5.30	5.52	5.70	5.99	6.21
ANTILOG(INTENSITY):	49.90	100.48	149.90	200.34	249.64	298.87	399.41	497.70
SOURCE 1 1 E(NO/YR):	.110E-02	.376E-04	.317E-05	.395E-06	.682E-07	.145E-07	.947E-09	.992E-10
SOURCE 1 2 E(NO/YR):	.175E-02	.708E-04	.672E-05	.917E-06	.170E-06	.382E-07	.275E-08	.309E-09
SOURCE 1 3 E(NO/YR):	.786E-02	.473E-03	.638E-04	.118E-04	.281E-05	.787E-06	.827E-07	.126E-07
SOURCE 1 4 E(NO/YR):	.206E-01	.159E-02	.272E-03	.615E-04	.174E-04	.564E-05	.757E-06	.140E-06
SOURCE 1 5 E(NO/YR):	.925E-02	.685E-03	.111E-03	.241E-04	.657E-05	.206E-05	.260E-06	.459E-07
SOURCE 2 1 E(NO/YR):	.761E-02	.703E-03	.145E-03	.391E-04	.128E-04	.466E-05	.764E-06	.164E-06
CAUTION: NUMERICAL INTEGRATION ERROR IN AREA IS -8.31 % FOR (OUTSIDE) SOURCE 2 2								
SOURCE 2 2 E(NO/YR):	.473E-01	.491E-02	.122E-02	.400E-03	.158E-03	.691E-04	.157E-04	.444E-05
SOURCE 3 1 E(NO/YR):	-.271E+00	-.233E-01	-.449E-02	-.114E-02	-.355E-03	-.126E-03	-.197E-04	-.411E-05
(BACKGROUND) E(NO/YR):	.469E+00	.331E-01	.572E-02	.136E-02	.411E-03	.142E-03	.216E-04	.446E-05
ALL SOURCES E(NO/YR):	.294E+00	.183E-01	.306E-02	.764E-03	.253E-03	.985E-04	.195E-04	.515E-05
ALL SOURCES RISK:	.255E+00	.181E-01	.305E-02	.764E-03	.253E-03	.985E-04	.195E-04	.516E-05

RISKS:	0.100000	0.020000	0.010000	0.005000
INTENSITY:	4.16	4.58	4.74	4.90
ANTILOG(INTENSITY):	63.90	97.87	114.81	134.16

END OF JOB

APPENDIX C

PROGRAM LISTING

```
      C        MAINROUTINE
      C        R K MCGUIRE   U.S.G.S. JANUARY 1975
      C       PLANAR VERSION (CARTESIAN COORDINATES)
      C
      C   INTERNAL SOURCE AREA SIDE AND CORNER NOTATION FOLLOWS......
      C
      C                     SIDE 4
      C      (X3,Y3)------------------(X4,Y4)
      C             '                  '
      C             '                  '
      C             '                  '
      C             '                  '
      C SIDE 3      '                  ' SIDE 2
      C             '                  '
      C             '                  '
      C             '                  '
      C             '                  '
      C      (X1,Y1)------------------(X2,Y2)
      C                     SIDE 1
      C
      C
            COMMON NRD,NWR,NLEI,TI(12),RSKTI(12)
            COMMON C1,C2,C3,SIG,RZERO,RONE,AAA,BBB
            COMMON NGS,NRS(10),AM0(11),AM1(11),LORS(11)
            COMMON BETA(11),RATE(11),COEF(11),FDEPTH(11)
            COMMON NSTEP0,NSTEP1,JCALC,JPRNT
            COMMON INDIC(4),AREA(10,11),X(10,11,2),Y(10,11,2)
            DIMENSION TITLE(20)
            DIMENSION RISKS(9),ATI(12),BRISK(12),TIF(8)
      C         TO MODIFY LIMITS AS STATED IN PROGRAM DOCUMENTATION, CHANGE
      C         COMMON DIMENSION STATEMENTS IN MAIN PROGRAM AND SUBROUTINES
      C         FOLLOWS:
      C         (1) TO CHANGE MAX. NO. OF GROSS SOURCES (PRESENTLY 10):
      C             (A) CHANGE ALL 10'S TO NEW MAX.
      C             (B) CHANGE ALL 11'S IN SINGLE DIMENSION ARRAYS TO
      C                  NEW MAXIMUM + 1.
      C         (2) TO CHANGE MAX. NO. OF SUBSOURCES IN EACH GROSS SOURCE
      C                (PRESENTLY 10):
      C             (A) CHANGE ALL 11'S IN DOUBLE- AND TRIPLE-DIENSION ARRA
      C                 TO NEW MAXIMUM + 1.
      C         (3) TO CHANGE MAX. NO. IN THE LIST OF EXAMINED INTENSITIES
      C                (PRESENTLY 12):
      C             (A) CHANGE ALL 12'S TO NEW MAXIMUM.
      C         (4) TO CHANGE MAX. NO. OF INPUT RISK LEVELS (PRESENTLY 8):
      C             (A) CHANGE 9 TO NEW MAX. + 1
      C             (B) CHANGE STATEMENT BELOW: 'RISKS(9)=0.0'
      C                 TO 'RISKS(NEW MAX. + 1) = 0.0'.
            NRD=5
            NWR=6
      C        READ TITLE
            READ (NRD,900) (TITLE(I),I=1,20)
        900 FORMAT (20A4)
            WRITE (NWR,910) (TITLE(I),I=1,20)
        910 FORMAT (10X,20A4)
      C          READ STEP SIZE AND SWITCH VALUES.
```

```
      READ (NRD,921) NSTEP,JCALC,JPRNT
  921 FORMAT (3I10)
      WRITE(NWR,922) NSTEP,JCALC,JPRNT
  922 FORMAT (/' NSTEP = ',I5,' JCALC = ',I5,' JPRNT = ',I5)
C          NSTEPO IS STEP SIZE USED WHEN SITE IS OUTSIDE
C                 (QUADRILATERAL) SOURCE BEING CONSIDERED.
C          NSTEPI IS STEP SIZE USED WHEN SITE IS INSIDE
C                 (QUADRILATERAL) SOURCE BEING CONSIDERED.
      NSTEPO=NSTEP
      NSTEPI=NSTEP
C          READ NUMBER AND LIST OF EXAMINED INTENSITIES.
      READ (NRD,901) NLEI,(TI(I),I=1,NLEI)
  901 FORMAT(I5,12F5.3)
      WRITE (NWR,902) (TI(I),I=1,NLEI)
  902 FORMAT (/' LIST OF EXAMINED INTENSITIES ',12F8.2)
  903 FORMAT(8F10.2)
      DO 90 I=1,NLEI
      ATI(I)=EXP(TI(I))
   90 BRISK(I)=0.0
C         READ LIFETIME AND RISKS DESIRED.
      READ (NRD,903) (RISKS(I),I=1,8)
      WRITE(NWR,919) (RISKS(I),I=1,8)
  919 FORMAT(/' RISKS DESIRED ',8F8.4)
C        READ ATTENUATION DATA
      READ (NRD,920) C1,C2,C3,SIG,RZERO,RONE,AAA,BBB
  920 FORMAT (8F10.2)
      WRITE (NWR,905)C1,C2,C3,SIG,RZERO,RONE,AAA,BBB
  905 FORMAT(/' ATTENUATION DATA:   C1       C2       C3       '
     1,'SIGMA   RZERO    RONE      AAA      BBB',/16X,8F8.2)
      IF (BBB+0.00001) 101,102,102
  101 WRITE (NWR,924)
  924 FORMAT(//' INPUT ERROR:  THE VALUE OF BBB MUST BE POSITIVE,'
     1 ' BETWEEN 0.0 AND THE VALUE OF C2. EXECUTION STOPPED.')
      GO TO 890
  102 IF (C2-BBB) 101,103,103
C         IF BBB=0.0, SET EQUAL TO A SMALL NUMBER
  103 IF (BBB-0.00001) 104,105,105
  104 BBB=0.0000000001
C        READ SOURCE DATA
  105 READ (NRD,906) NGS,(NRS(I),I=1,NGS)
  906 FORMAT (16I5)
      WRITE (NWR,907) NGS,(NRS(I),I=1,NGS)
  907 FORMAT(/' NO. OF GROSS SOURCES ',I5/' NO. OF SUBSOURCES IN GROSS
     1OURCES ',16I5)
      WRITE (NWR,918)
  918 FORMAT (/' GROSS SOURCE   L/S',5X,'COEF',7X,
     1'M0',8X,'M1',6X,'BETA',5X,'RATE/YR',3X,'FDEPTH')
      NGS1=NGS+1
      DO 110 I=1,NGS1
      READ(NRD,904)LORS(I),COEF(I),AM0(I),AM1(I),BETA(I),RATE(I),
     1 FDEPTH(I)
  904 FORMAT(I10,6F10.2)
      IF (I-NGS1) 110,120,120
  110 WRITE (NWR,908)I,LORS(I),COEF(I),AM0(I),AM1(I),BETA(I),RATE(I),
     1 FDEPTH(I)
```

```
  908 FORMAT (1X,I7,3X,I7,3F10.2,3F10.4)
C         WRITE BACKGROUND SEISMICITY
  120 WRITE (NWR,925) LORS(I),COEF(I),AM0(I),AM1(I),BETA(I),RATE(I),
     1 FDEPTH(I)
  925 FORMAT(' (BACKGROUND)',I5,3F10.2,3F10.4/)
      DO 200 II=1,NGS
      NRSII=NRS(II)+1
      DO 150 JJ=1,NRSII
      READ (NRD,903) X(II,JJ,1),Y(II,JJ,1),X(II,JJ,2),Y(II,JJ,2)
      WRITE (NWR,909) II,X(II,JJ,1),Y(II,JJ,1),X(II,JJ,2),Y(II,JJ,2)
  909 FORMAT(' GROSS SOURCE',I3,' SUBSOURCE COORDINATE DATA ',4F10.2)
  150 CONTINUE
  200 WRITE (NWR,932)
  932 FORMAT(1X)
C        CALCULATE AREA OF EACH SUBSOURCE AND GROSS SOURCE.
C        IF ARRAYS X( ) AND Y( ) CONTAIN LONGITUDE
C          AND LATITUDE, CHANGE SUBROUTINE 'AREAS' TO
C          CALCULATE CORRECT AREAS USING THESE PARAMETERS.
C          SEE ALSO REQUIRED CHANGES BELOW.
      DO 400 II=1,NGS
      NTOT=NRS(II)+1
      AREA(II,NTOT)=0.0
      DO 300 JJ=1,NRS(II)
      CALL AREAS(X(II,JJ,1),Y(II,JJ,1),X(II,JJ,2),Y(II,JJ,2),
     1 X(II,JJ+1,1),Y(II,JJ+1,1),X(II,JJ+1,2),Y(II,JJ+1,2),AREA(II,JJ
      WRITE (NWR,911) II,JJ, AREA(II,JJ)
  911 FORMAT(' GROSS SOURCE',I3,' SUBSOURCE',I3,' EXACT AREA',F10.1)
  300 AREA(II,NTOT)=AREA(II,NTOT)+AREA(II,JJ)
  400 WRITE (NWR,913) II,AREA(II,NTOT)
  913 FORMAT(' GROSS SOURCE',I3,13X,' TOTAL AREA',F10.1/)
C         COMPUTE BACKGROUND SEISMICITY
      IF(RATE(NGS1)-0.0000000001) 420,420,405
C         RBACK IS RADIUS OUT TO WHICH RISK FROM
C           BACKGROUND SEISMICITY IS CALCULATED.
  405 RBACK=150.
C        FOR BACKGROUND SEISMICITY, NSTEPI IS DOUBLED (AND
C           THEN HALVED AFTER CALCULATIONS).
      NSTEPI=2*NSTEPI
      CALL CIRCLE(RBACK,NGS1,1.,BRISK)
      NSTEPI=NSTEPI/2
      DO 410 I=1,NLEI
  410 BRISK(I)=COEF(NGS1)*BRISK(I)/10000.
      WRITE(NWR,926)(TI(I),I=1,NLEI)
  926 FORMAT(/' RESULTS FOR BACKGROUND SEISMICITY'/13X,'INTENSITY:  '
     1 F7.2,11(2X,F7.2))
      WRITE(NWR,923)(ATI(I),I=1,NLEI)
      WRITE(NWR,927)(BRISK(I),I=1,NLEI)
  927 FORMAT(' (BACKGROUND) E(NO/YR): ',12E9.3)
C         LOOP ON SETS OF SITES FOR ANALYSIS
  420 READ (NRD,914) NX,NY,XZERO,YZERO,XDELTA,YDELTA
  914 FORMAT (2I5,4F10.2)
      IF (NX) 850,850,430
  430 DO 800 IY=1,NY
      YNOT=YZERO+(IY-1)*YDELTA
      DO 700 IX=1,NX
```

```
      XNOT=XZERO+(IX-1)*XDELTA
      DO 450 I=1,NLEI
  450 RSKTI(I)=BRISK(I)
      WRITE (NWR,915) XNOT,YNOT,(TI(I),I=1,NLEI)
  915 FORMAT(///' RESULTS FOR SITE LOCATION ',2F10.2/
     1 /13X,'INTENSITY:  ',F7.2,11(2X,F7.2))
      WRITE (NWR,923) (ATI(I),I=1,NLEI)
  923 FORMAT (4X,'ANTILOG(INTENSITY):  ',F7.2,11(2X,F7.2))
      DO 600 II=1,NGS
      DO 500 JJ=1,NRS(II)
      INGS=II
      INSS=JJ
C          IF THE USER WISHES THIS PROGRAM TO WORK ON LONGITUDE AND
C          LATITUDE COORDINATES, SIMPLY INPUT THESE COORDINATES AS IN T
C          CARTESIAN CASE; AT THIS POINT CALCULATE (IN UNITS
C          CONSISTENT WITH THE ATTENUATION FUNCTION) THE CARTESIAN
C          LOCATION OF X(II,JJ,1),Y(II,JJ,1) WITH RESPECT TO XNOT,YNOT,
C          AND SIMILARLY WITH THE OTHER 3 POINTS DESCRIBING THE SOURCE
C          AREA UNDER CONSIDERATION, AND PLACE THESE CALCULATED CARTESI
C          COORDINATES IN THE ARGUMENT LIST OF THE FOLLOWING CALL STATE
C          MENT (WITH XNOT AND YNOT AS THE ORIGIN, I.E. (0.0,0.0)).
C          SEE ALSO CHANGES REQUIRED ABOVE FOR SUBROUTINE 'AREAS'.
      CALL RRISK(XNOT,YNOT,INGS,INSS,X(II,JJ,1),Y(II,JJ,1),X(II,JJ,
     X2),Y(II,JJ,2),X(II,JJ+1,1),Y(II,JJ+1,1),X(II,JJ+1,2),Y(II,JJ+1,2
  500 CONTINUE
  600 CONTINUE
      IF (JPRNT) 615,615,610
  610 WRITE(NWR,927)(BRISK(I),I=1,NLEI)
  615 WRITE (NWR,916) (RSKTI(I),I=1,NLEI)
  916 FORMAT (' ALL SOURCES  E(NO/YR): ',12E9.3)
      DO 620 I=1,NLEI
  620 RSKTI(I)=1.-EXP(-RSKTI(I))
      WRITE (NWR,931) (RSKTI(I),I=1,NLEI)
  931 FORMAT(' ALL SOURCES      RISK: ',12E9.3)
C          ESTIMATE INTENSITIES AT RISKS DESIRED.
      RISKS(9)=0.0
      IA=0
      IF(RISKS(1)-0.0000000001) 700,700,625
  625 DO 630 IRK=1,8
      IF (RISKS(IRK)-RSKTI(1)) 640,640,630
  630 TIF(IRK)=1000000.
      GO TO 700
  640 IA=IA+1
      IF (IA-NLEI) 650,645,645
  645 TIF(IRK)=1000000.
      IRK=IRK+1
      IF (RISKS(IRK)-0.0000000001)680,680,645
  650 IF(RISKS(IRK)-RSKTI(IA+1))640,655,655
  655 TIF(IRK)=(ALOG(RSKTI(IA)/RISKS(IRK)))
     1  /(ALOG(RSKTI(IA)/RSKTI(IA+1)))
      TIF(IRK)=TI(IA)+TIF(IRK)*(TI(IA+1)-TI(IA))
  658 IRK=IRK+1
      IF (RISKS(IRK)-0.0000000001)680,680,660
  660 IF(RISKS(IRK)-RSKTI(IA+1)) 640,655,655
  680 IRK=IRK-1
```

```
          WRITE(NWR,928)(RISKS(I),I=1,IRK)
      928 FORMAT(/16X,' RISKS: ',8F9.6)
          WRITE(NWR,929)(TIF(I),I=1,IRK)
      929 FORMAT(13X,'INTENSITY: ',8F9.2)
          DO 685 I=1,IRK
          IF (TIF(I)-999999.)683,685,685
      683 TIF(I)=EXP(TIF(I))
      685 CONTINUE
          WRITE (NWR,930)(TIF(I),I=1,IRK)
      930 FORMAT(4X,'ANTILOG(INTENSITY): ',8F9.2)
      700 CONTINUE
      800 CONTINUE
          GO TO 420
      850 WRITE (NWR,917)
      917 FORMAT ('/////'        END OF JOB ' //)
      890 CALL EXIT
          END


          SUBROUTINE RRISK(XNOT,YNOT,INGS,INSS,
         1 X1,Y1,X2,Y2,X3,Y3,X4,Y4)
          COMMON NRD,NWR,NLEI,TI(12),RSKTI(12)
          COMMON C1,C2,C3,SIG,RZERO,RONE,AAA,BBB
          COMMON NGS,NRS(10),AM0(11),AM1(11),LORS(11)
          COMMON BETA(11),RATE(11),COEF(11),FDEPTH(11)
          COMMON NSTEPO,NSTEPI,JCALC,JPRNT
          COMMON INDIC(4),AREA(10,11)
          DIMENSION XL(4),YL(4),XR(4),YR(4),AA(4),BB(4)
C             SUBROUTINE WHICH LOADS TEMPORARY ARRAYS WITH THIS
C               SUBSOURCE'S CORNERS AND DETERMINES IF THIS SITE IS
C               WITHIN OR WITHOUT THE SUBSOURCE.
          XL(1)=X1
          YL(1)=Y1
          XR(1)=X2
          YR(1)=Y2
          XL(2)=X2
          YL(2)=Y2
          XR(2)=X4
          YR(2)=Y4
          XL(3)=X3
          YL(3)=Y3
          XR(3)=X1
          YR(3)=Y1
          XL(4)=X4
          YL(4)=Y4
          XR(4)=X3
          YR(4)=Y3
C            DETERMINE IF ANY SIDES ARE VERTICAL LINES
          DO 200 II=1,4
          DIF=XL(II)-XR(II)
          IF (DIF) 140,180,160
      140 IF (DIF+0.01) 190,190,180
      160 IF (DIF-0.01) 180,190,190
C            INDIC(I)=1  IMPLIES NOT A VERTICAL LINE
C            INDIC(I)=2  IMPLIES A VERTICAL LINE (INFINITE SLOPE).
```

```
 180  INDIC(II)=2
      AA(II)=0.
      BB(II)=0.
      GO TO 200
 190  INDIC(II)=1
      AA(II)=(YL(II)-YR(II))/(XL(II)-XR(II))
      BB(II)=YL(II)-AA(II)*XL(II)
C          AA(II) IS SLOPE OF II'TH SIDE
C          BB(II) IS INTERCEPT OF II'TH SIDE
  200  CONTINUE
C        DETERMINE IF SITE IS INSIDE SOURCE AREA.
      DO 220 II=1,4
      IJ=5-II
      GO TO (210,215),INDIC(II)
 210  DIFNOT=YNOT-AA(II)*XNOT-BB(II)
      DIF=YL(IJ)-AA(II)*XL(IJ)-BB(II)
 211  IF (DIF) 214,214,212
 212  IF (DIFNOT) 400,400,220
 214  IF (DIFNOT) 220,400,400
 215  DIF=XL(IJ)-XL(II)
      DIFNOT=XNOT-XL(II)
      GO TO 211
 220  CONTINUE
C        IF DO LOOP FINISHED, POINT LIES WITHIN AREA.
      CALL INSIDE(XNOT,YNOT,INGS,INSS,XL,YL,XR,YR,AA,BB)
      GO TO 900
 400  CALL OUTSID(XNOT,YNOT,INGS,INSS,XL,YL,XR,YR,AA,BB)
 900  RETURN
      END
```

```
      SUBROUTINE OUTSID(XNOT,YNOT,INGS,INSS,XL,YL,XR,YR,AA,BB)
      COMMON NRD,NWR,NLEI,TI(12),RSKTI(12)
      COMMON C1,C2,C3,SIG,RZERO,RONE,AAA,BBB
      COMMON NGS,NRS(10),AM0(11),AM1(11),LORS(11)
      COMMON BETA(11),RATE(11),COEF(11),FDEPTH(11)
      COMMON NSTEPO,NSTEPI,JCALC,JPRNT
      COMMON INDIC(4),AREA(10,11)
      DIMENSION XL(4),YL(4),XR(4),YR(4),AA(4),BB(4),XC(4),YC(4)
      DIMENSION RSK(12)
C          SUBROUTINE FOR CALCULATING RISK WHEN SITE IS OUTSIDE
C          (QUADRILATERAL) SOURCE AREA.
C          DEFINE DISTANCE VALUES TO SELECT STEP SIZE.
C          (RC IS CLOSEST DISTANCE BETWEEN SITE AND SOURCE.)
C          RC BETWEEN 0.0 AND RZ1 INPLIES STEP SIZE = NSTEPO.
C          RC BETWEEN RZ1 AND RZ2 IMPLIES STEP SIZE = NSTEPO/2.
C          RC BETWEEN RZ2 AND RZ3 IMPLIES LUMP RISK
C                AT CENTER OF SOURCE (DEFINED BY AVERAGING LOCATIONS
C                OF CORNER POINTS).
C          RC GREATER THAN RZ3 IMPLIES IGNORE SOURCE.
      RZ1=100.
      RZ2=300.
      RZ3=500.
C          TO BY-PASS THIS ALGORITHM, SET RZ1 TO A LARGE NUMBER.
C          TO PRODUCE 0-1 ALGORITHM (DISREGARD, OR CALCULATE USING
```

```
C           NSTEPO), SET RZ1=RZ2=RZ3=DISTANCE WITHIN WHICH YOU
C           WISH TO CONSIDER RISK.
C         FIND CLOSEST (IC,RC) AND FARTHEST (IF,RF) POINTS AND DISTANC
      RC2=10000000000.
      RF2=0.
      DO 108 II=1,4
      DIST=(XNOT-XL(II))*(XNOT-XL(II))+(YNOT-YL(II))*(YNOT-YL(II))
      IF (RC2-DIST) 104,104,102
  102 RC=SQRT(DIST)
      RC2=DIST
      IC=II
  104 IF (DIST-RF2) 108,108,106
  106 RF=SQRT(DIST)
      RF2=DIST
      IF=II
  108 CONTINUE
      ICS=0
C         SEE IF ANY SIDE LIES CLOSER THAN CLOSEST POINT
      DO 150 II=1,4
C        IS SLOPE INFINITE?
      GO TO (130,121),INDIC(II)
  121 XS=XL(II)
      YS=YNOT
      GO TO 145
C        IS SLOPE ZERO?
  130 IF (AA(II)-0.001) 131,140,140
  131 IF (AA(II)+0.001) 140,140,132
  132 XS=XNOT
      YS=YL(II)
      GO TO 145
C         SLOPE IS NOT ZERO, SO CALCULATE NEAREST POINT.
  140 XS=(YNOT+(XNOT/AA(II))-BB(II))/(AA(II)+(1./AA(II)))
      YS=((XNOT-XS)/AA(II))+YNOT
  145 CALL BETWEN(XL(II),YL(II),XR(II),YR(II),XS,YS,INDIC(II),IANS)
      IF (IANS) 150,146,148
  146 NERROR=1
      GO TO 800
  148 DIST=(XNOT-XS)*(XNOT-XS)+(YNOT-YS)*(YNOT-YS)
      IF (DIST-RC2) 149,150,150
  149 RC2=DIST
      RC=SQRT(DIST)
      ICS=II
  150 CONTINUE
      APPROX=0.0
      DO 290 II=1,NLEI
  290 RSK(II)=0.
C          DETERMINE STEP SIZE FROM RZ1,RZ2, AND RZ3.
      IF (RC-RZ1) 308,308,292
  292 IF (RC-RZ2) 294,294,296
  294 NSTEPX=NSTEPO/2
      GO TO 310
  296 IF (RC-RZ3) 298,298,850
C           IF RC IS BETWEEN RZ2 AND RZ3, CALCULATE RISK
C           ASSUMING SEISMICITY IS LUMPED AT CENTER (AVERAGE
C           OF CORNER POINTS).
```

```
  298 XAVE=(XL(1)+XL(2)+XL(3)+XL(4))/4.
      YAVE=(YL(1)+YL(2)+YL(3)+YL(4))/4.
      R=SQRT((XAVE-XNOT)*(XAVE-XNOT)+(YAVE-YNOT)*(YAVE-YNOT))
      NTOT=NRS(INGS)+1
      RATEI=RATE(INGS)*AREA(INGS,INSS)/AREA(INGS,NTOT)
      DO 306 JJ=1,NLEI
      IF (JCALC) 300,302,302
  300 CALL RISK1(TI(JJ),R,INGS,RISK)
      GO TO 304
  302 CALL RISK2(TI(JJ),R,INGS,RISK)
  304 IF (RISK-0.0000000001) 600,600,305
  305 RSK(JJ)=COEF(INGS)*RISK*RATEI
  306 RSKTI(JJ)=RSKTI(JJ) + RSK(JJ)
      GO TO 600
  308 NSTEPX=NSTEPO
  310 AN=NSTEPX
      STSIZE=(RF-RC)/AN
C        STEP THRU SOURCE AREA.
      DO 500 ISTEP=1,NSTEPX
      AI=ISTEP
      R=RC+(AI-0.5)*STSIZE
      NPT=0
      ANGLE=0.
      SIGNAL=1.
C        LOOP ON EACH SIDE
      DO 400 II=1,4
      GO TO (330,320),INDIC(II)
C           SIDE II IS A VERTICAL LINE
C           DOES CIRCLE (RADIUS R) INTERSECT IT?
  320 A=XL(II)-XNOT
      IF (A) 322,322,323
  322 IF (R+A) 400,400,324
  323 IF (R-A) 400,400,324
C           COMPUTE TWO INTERSECTION POINTS
  324 X1=XL(II)
      B=SQRT(R*R-(X1-XNOT)*(X1-XNOT))
      Y1=YNOT+B
      X2=XL(II)
      Y2=YNOT-B
      GO TO 341
  330 A=1.+AA(II)*AA(II)
      B=2.*(-XNOT+AA(II)*(BB(II)-YNOT))
      C=XNOT*XNOT+YNOT*YNOT+BB(II)*(BB(II)-2.*YNOT)-R*R
      D=B*B-4.*A*C
      IF (D) 400,400,340
C        TWO INTERSECTIONS, CALCULATE FIRST INTERSECTION POINT.
  340 D=SQRT(D)
      X1=(-B+D)/(2.*A)
      Y1=AA(II)*X1 + BB(II)
      X2=(-B-D)/(2.*A)
      Y2=AA(II)*X2+BB(II)
C        SEE IF (X1,Y1) IS ON BOUNDARY
  341 CALL BETWEN(XL(II),YL(II),XR(II),YR(II),X1,Y1,INDIC(II),IANS)
      IF (IANS) 360,342,345
  342 NERROR=4
```

```
      GO TO 800
C        CALCULATE OTHER POINT, SEE IF IS ON BOUNDARY.
  345 CALL BETWEN(XL(II),YL(II),XR(II),YR(II),X2,Y2,INDIC(II),IANS)
      IF (IANS) 348,346,350
  346 NERROR=5
      GO TO 800
C        STORE FIRST POINT
  348 NPT=NPT+1
      XC(NPT)=X1
      YC(NPT)=Y1
      GO TO 400
C        SEE IF THIS SIDE IS CLOSEST TO POINT, IF SO, TREAT SPECIALLY.
  350 IF (II-ICS) 352,355,352
C           BOTH POINTS ARE ON BOUNDARY, CALCULATE ANGLE BETWEN THEM.
  352 SIGN=-1.
      GO TO 357
  355 SIGN=1.
      SIGNAL=-1.
  357 AD=SQRT((X1-X2)*(X1-X2)+(Y1-Y2)*(Y1-Y2))
      IF (AD-2.*R) 358,359,359
  358 ANGLE=SIGN*2.*ASIN(AD/(2.*R)) + ANGLE
      GO TO 400
  359 ANGLE=3.1415926536 +ANGLE
      GO TO 400
C        SEE IF SECOND POINT ONLY IS ON BOUNDARY
  360 CALL BETWEN(XL(II),YL(II),XR(II),YR(II),X2,Y2,INDIC(II),IANS)
      IF (IANS) 400,362,370
  362 NERROR=6
      GO TO 800
  370 NPT=NPT+1
      XC(NPT)=X2
      YC(NPT)=Y2
  400 CONTINUE
      GO TO (410,420,410,440),NPT
      IF (SIGNAL)460,405,405
  405 NERROR=7
      GO TO 800
  410 NERROR=8
      GO TO 800
  420 AD=SQRT((XC(1)-XC(2))*(XC(1)-XC(2))+(YC(1)-YC(2))*(YC(1)-YC(2)))
      ANGLE=ANGLE + SIGNAL*2.*ASIN(AD/(2.*R))
      GO TO 460
C           FOUR INTERSECTION POINTS (EACH ON A DIFFERENT SIDE).
C           DETERMINE ANGLE BY FINDING CLOSEST 2 INTERSECTIONS TO
C           FARTHEST CORNER, CALCULATE ANGLE BETWEEN, AND ADD ANGLE
C           BETWEEN OTHER TWO INTERSECTIONS.
  440 DIST1=1000000000.
      I1=0
      I2=0
      I3=0
      I4=0
      DO 450 JJ=1,4
      DIST=(XL(IFAR)-XC(JJ))*(XL(IFAR)-XC(JJ))
     1  +(YL(IFAR)-YC(JJ))*(YL(IFAR)-YC(JJ))
      IF (DIST-DIST1) 442,444,444
```

```
 442  DIST2=DIST1
      DIST1=DIST
      I4=I3
      I3=I2
      I2=I1
      I1=JJ
      GO TO 450
 444  IF (DIST-DIST2) 445,446,446
 445  DIST2=DIST
      I4=I3
      I3=I2
      I2=JJ
      GO TO 450
 446  I4=I3
      I3=JJ
 450  CONTINUE
C           CALCULATE ANGLE BETWEEN 2 CLOSEST POINTS TO FARTHEST CORNE
      AD=SQRT((XC(I1)-XC(I2))*(XC(I1)-XC(I2))
     1  + (YC(I1)-YC(I2))*(YC(I1)-YC(I2)))
      ANGLE=2.*ASIN(AD/(2.*R))
C         CALCULATE ANGLE BETWEEN 2 POINTS FARTHEST FROM
C         FARTHEST CORNER AND ADD TO PREVIOUS ANGLE.
      AD=SQRT((XC(I3)-XC(I4))*(XC(I3)-XC(I4))
     1  +(YC(I3)-YC(I4))*(YC(I3)-YC(I4)))
      ANGLE=2.*ASIN(AD/(2.*R)) + ANGLE
 460  CONTINUE
C        ANGLE FOR THIS RADIUS NOW KNOWN, CALCULATE RISK.
C        COMPUTE RATE OF EARTHQUAKES IN THIS ANNULAR SOURCE
      ANAREA=ANGLE*R*STSIZE
      APPROX=APPROX+ANAREA
      NTOT=NRS(INGS)+1
      RATEI=RATE(INGS)*ANAREA*AREA(INGS,INSS)/AREA(INGS,NTOT)
C        CALCULATE CONTRIBUTION TO RISK
      DO 480 JJ=1,NLEI
      IF (JCALC) 470,470,475
 470  CALL RISK1(TI(JJ),R,INGS,RISK)
      GO TO 478
 475  CALL RISK2(TI(JJ),R,INGS,RISK)
 478  IF (RISK-0.0000000001) 500,490,490
 490  RSK(JJ)=RSK(JJ)+RISK*RATEI
 480  CONTINUE
 500  CONTINUE
      ARERR=((APPROX-AREA(INGS,INSS))/AREA(INGS,INSS))*100.
      IF (ARERR-5.) 510,520,520
 510  IF (ARERR+5.) 520,520,540
 520  WRITE(NWR,903) ARERR,INGS,INSS
 903  FORMAT(10X,'CAUTION: NUMERICAL INTEGRATION ERROR IN AREA IS ',
     1 F6.2,' % FOR (OUTSIDE) SOURCE ',2I3)
C          NORMALIZE BY COMPUTED (APPROXIMATE) AREA
 540  DO 550 JJ=1,NLEI
      RSK(JJ)=COEF(INGS)*RSK(JJ)/APPROX
 550  RSKTI(JJ)=RSKTI(JJ)+RSK(JJ)
 600  IF (JPRNT) 850,850,610
C         PRINT RISKS FOR THIS SOURCE
 610  WRITE(NWR,902) INGS,INSS,(RSK(I),I=1,NLEI)
```

```
  902 FORMAT(' SOURCE',2I3,' E(NO/YR): ',12E9.3)
      GO TO 850
C        ERROR PRINTOUT
  800 WRITE(NWR,901)NERROR,INGS,INSS,IC,RC,XNOT,YNOT,(XL(I),YL(I),I=1,
     1 , R,ANGLE,RC,RF,(XC(I),YC(I),I=1,4)
  901 FORMAT(' ***** ERROR',I4,' IN SUBROUTINE OUTSID. SOURCE NO.',2I
     1' DEBUG VALUES FOLLOW.....',/10X,2I5,5(/10X,4F14.6))
  850 RETURN
      END
```

```
      SUBROUTINE RISK1(TIC,REPIS,INGS,RISK)
      COMMON NRD,NWR,NLEI,TI(12),RSKTI(12)
      COMMON C1,C2,C3,SIG,RZERO,RONE,AAA,BBB
      COMMON NGS,NRS(10),AM0(11),AM1(11),LORS(11)
      COMMON BETA(11),RATE(11),COEF(11),FDEPTH(11)
      COMMON NSTEPO,NSTEPI,JCALC,JPRNT
      COMMON INDIC(4),AREA(10,11)
C
C          SUBROUTINE TO CALCULATE RISK WHEN THE FOLLOWING SPECIAL
C          FORM OF ATTENUATION FUNCTION IS USED:
C               I = C1 + C2*M + C3*ALOG(R+RZERO)
C
      SIGG=SIG
      RFOC=SQRT(REPIS*REPIS + FDEPTH(INGS)*FDEPTH(INGS))
      IF (RFOC-RONE) 10,10,20
   10 R=RONE
C         IF DIFFERENT STANDARD DEVIATION INSIDE RADIUS RONE IS
C         DESIRED, SET SIGG TO THIS STANDARD DEVIATION HERE.
      GO TO 30
   20 R=RFOC
   30 RLN=ALOG(R+RZERO)
C
C          IS THIS LOOSE OR STRICT SOURCE?
C          IF STRICT, RISK COMPUTED IS THAT FOR A SINGLE EARTHQUAKE
C          WITH (EXPONENTIALLY-DISTRIBUTED) RANDOM MAGNITUDE
C          (OR INTENSITY) BETWEEN AM0 AND AM1.  IF A LOOSE
C          SOURCE, RISK COMPUTED IS THAT FOR 'ANEQ' EARTHQUAKES
C          WITH (EXPONENTIALLY-DISTRIBUTED) RANDOM MAGNITUDE
C          (OR INTENSITY) BETWEEN 0.0 AND AM1, WITH 'ANEQ' CALCULATED
C          SO THAT THE EXPECTED NUMBER OF EVENTS BETWEEN AM0 AND AM1
C          IS UNITY.
C
      IF (LORS(INGS)) 40,40,50
   40 AK=1./(1.-EXP(-BETA(INGS)*AM1(INGS)))
      ANEQ=1./(1.-AK+AK*EXP(-BETA(INGS)*AM0(INGS)))
      AMZ=0.0
      GO TO 60
   50 AK=1./(1.-EXP(-BETA(INGS)*(AM1(INGS)-AM0(INGS))))
      ANEQ=1.
      AMZ=AM0(INGS)
C          CALCULATE MAGNITUDE 'AMSTAR' ASSOCIATED WITH MAX. INTENSITY
C          AT THIS DISTANCE (R); IF LESS THAN AM1, EVALUATE RISK
C          FOR MAGNITUDES BETWEEN AMSTAR AND AM1 SEPARATELY.
   60 AMSTAR=(AAA-C1-C3*RLN)/(C2-BBB)
```

```
      IF (AM1(INGS)-AMSTAR) 65,65,70
C          NONE OF MAGNITUDE INTEGRATION LIES ABOVE AMSTAR.
   65 CALL ERISK(AMZ,AM1(INGS),C1,C2,C3,RLN,SIGG,BETA(INGS),TIC,
     1 G1,G2,G3,G4,CON1,CON2,CON3)
      GO TO 77
   70 IF (AMZ-AMSTAR) 80,75,75
C          ALL OF MAGNITUDE INTEGRATION LIES ABOVE AMSTAR.
   75 CALL ERISK(AMZ,AM1(INGS),AAA,BBB,0.,RLN,SIGG,BETA(INGS),TIC,
     1  G1,G2,G3,G4,CON1,CON2,CON3)
   77 RISK=((1.-AK)*G1 + AK*G2 + AK*(G3-G4)*CON1*CON2)*ANEQ
      GO TO 100
C          SOME OF MAGNITUDE INTEGRATION LIES ABOVE MSTAR, SOME BELOW.
   80 CALL ERISK(AMZ,AMSTAR,C1,C2,C3,RLN,SIGG,BETA(INGS),TIC,
     1  G1,G2,G3,G4,CON1,CON2,CON3)
      CALL ERISK(AMSTAR,AM1(INGS),AAA,BBB,0.,RLN,SIGG,BETA(INGS),TIC,
     1  GG1,GG2,GG3,GG4,CCON1,CCON2,CCON3)
      RISK=((1.-AK)*G1 +AK*G2 +AK*(G3-G4)*CON1*CON2
     1  +(1.-AK)*(GG1-GG2) + AK*(GG3-GG4)*CCON1*CCON2
     2  *EXP(+BETA(INGS)*(AMZ-AMSTAR)))*ANEQ
  100 RETURN
      END
```

```
      SUBROUTINE ERISK(AMZ,AMM,C1,C2,C3,RLN,SIG,BETA,TIC,
     1  G1,G2,G3,G4,CON1,CON2,CON3)
C          EVALUATE RISK ASSOCIATED WITH EXPONENTIAL MAGNITUDE LAW
C              FOR MAGNITUDES BETWEEN AMZ AND AMM.
      Z=(TIC-C1-C2*AMM-C3*RLN)/SIG
      CALL NDTR(Z,G1,D)
      Z=Z-BETA*SIG/C2
      CALL NDTR(Z,G3,D)
      Z=(TIC-C1-C2*AMZ-C3*RLN)/SIG
      CALL NDTR(Z,G2,D)
      Z=Z-BETA*SIG/C2
      CALL NDTR(Z,G4,D)
      IF (C2-0.001) 10,10,20
   10 CON1=100000000.
      CON3=CON1
      GO TO 30
   20 CON1=((BETA*BETA*SIG*SIG)/(2.*C2*C2))+(BETA*AMZ)
     1 +((C1-TIC)*BETA/C2)
      CON3=CON1+BETA*(AMM-AMZ)
      CON1=EXP(CON1)
      CON3=EXP(CON3)
   30 CON2=BETA*C3/C2
      R=EXP(RLN)
      CON2=R**CON2
      RETURN
      END
```

```
      SUBROUTINE RISK2(TIC,REPIS,INGS,RISK)
      COMMON NRD,NWR,NLEI,TI(12),RSKTI(12)
      COMMON C1,C2,C3,SIG,RZERO,RONE,AAA,BBB
      COMMON NGS,NRS(10),AM0(11),AM1(11),LORS(11)
```

```
      COMMON BETA(11),RATE(11),COEF(11),FDEPTH(11)
      COMMON NSTEPO,NSTEPI,JCALC,JPRNT
      COMMON INDIC(4),AREA(10,11)
C
C         SUBROUTINE TO CALCULATE RISK WHEN AN ATTENUATION FUNCTION
C         NON-SEPARABLE IN M AND R IS USED, OR WHEN NON-EXPONENTIAL
C         DENSITY FUNCTION ON EARTHQUAKE SIZE IS USED, REQUIRING
C         NUMERICAL INTEGRATION ON MAGNITUDE.
C
C         THE EXAMPLE GIVEN HERE IS A SEPARABLE FUNCTION OF M AND R,
C         FOR WHICH SUBROUTINE RISK1 WOULD ACTUALLY BE USED IN
C         CALCULATIONS.  IT IS USED HERE FOR DEMONSTRATION PURPOSES
C         ONLY.
C
C         AMINT IS MAGNITUDE INTERVAL USED FOR NUMERICAL INTEGRATION.
C         NO. OF MAGNITUDE STEPS (E.G.(AM1-AM0)/AMINT) MUST BE
C         A WHOLE NUMBER.
C
      AMINT=0.05
      RISK=0.0
      SIGG=SIG
      RFOC=SQRT(REPIS*REPIS + FDEPTH(INGS)*FDEPTH(INGS))
      IF (RFOC-RONE) 80,80,90
   80 R=RONE
C         IF DIFFERENT STANDARD DEVVIATION INSIDE RADIUS RONE IS
C          DESIRED, SET SIGG TO THIS STANDARD DEVIATION HERE.
      GO TO 100
   90 R=RFOC
  100 IF (LORS(INGS)) 110,110,150
C         LOOSE SOURCE, COMPUTE APPROPRIATE RATE, ASSUMING
C         LOWEST MAGNITUDE = 4.0.
  110 AK=1./(1.-EXP(-BETA(INGS)*(AM1(INGS)-4.0)))
      ANEQ=1./(1.-AK+AK*EXP(-BETA(INGS)*(AM0(INGS)-4.0)))
      AMZ=4.0
      GO TO 200
  150 AMZ=AM0(INGS)
      ANEQ=1.
      AK=1./(1.-EXP(-BETA*(AM1(INGS)-AM0(INGS))))
C            COMPUTE NUMBER OF INTEGRATION STEPS
C            (STEPSIZE = AMINT MAGNITUDE UNITS).
  200 NMAGS=(AM1(INGS)-AMZ)/AMINT +0.1
C           LOOP ON MAGNITUDE, IN STEPS OF AMINT MAGNITUDE UNITS
      DO 500 IMAG=1,NMAGS
      AM=IMAG
      AMAG=AMZ+AM*AMINT-(AMINT/2.)
C         CALCULATE PROBABILITY OF EARTHQUAKE IN THIS MAGNITUDE STEP
      AMAGP=AMAG + (AMINT/2.)
      AMAGM=AMAG - (AMINT/2.)
      PROB=AK*(EXP(-BETA(INGS)*(AMAGM-AMZ))
     1  -EXP(-BETA(INGS)*(AMAGP-AMZ)))
C           CALCULATE MEAN INTENSITY FOR THIS MAGNITUDE (AND DISTANCE
C
C---------- USER:  INSERT YOUR MEAN FUNCTION HERE -------
      AMEAN = C1 + C2*AMAG + C3*ALOG(R+RZERO)
      IF (AMEAN-AAA-BBB*AMAG) 220,220,210
```

```
  210 AMEAN=AAA+BBB*AMAG
  220 CONTINUE
C          CALCULATE STANDARDIZED VARIABLE
      Z = (TIC-AMEAN)/SIGG
C             CALCULATE PROBABILITY OF EXCEEDING INTENSITY OF INTEREST
C --------    USER : INSERT YOUR (COMPLEMENTARY CUMULATIVE)
C                       PROBABILITY FUNCTION HERE -------
      CALL NDTR (Z,G,D)
C             ACCUMULATE RISK
  500 RISK = RISK + G*PROB
      RISK=RISK*ANEQ
      RETURN
      END
```

```
      SUBROUTINE BETWEN(X1,Y1,X2,Y2,XP,YP,INDIC,IANS)
C          SUBROUTINE TO DETERMINE IF (XP,YP) LIES BETWEEN
C              (X1,Y1) AND (X2,Y2).
      GO TO (100,200),INDIC
      GO TO 300
  100 IF (X1-XP) 110,410,120
  110 IF (X2-XP) 420,420,410
  120 IF (X2-XP) 410,420,420
  200 IF (Y1-YP) 210,410,220
  210 IF (Y2-YP) 420,420,410
  220 IF (Y2-YP) 410,420,420
C         ERROR RETURN
  300 IANS=0
      GO TO 500
C         (XP,YP) LIES BETWEEN END POINTS, I.E. ON SOURCE BOUNDARY
  410 IANS=1
      GO TO 500
C         (XP,YP) DOESN'T LIE BETWEEN END POINTS, I.E. IT'S OUTSIDE SOU
  420 IANS=-1
  500 RETURN
      END
```

```
      SUBROUTINE NDTR(X,P,D)
C          X  IS NO. OF STANDARDIZED NORMAL DEVIATES.
C          P  IS COMP. CUMULATIVE VALUE (OUTPUT).
C          D  IS DENSITY VALUE (OUTPUT)
      IF (X) 1,2,2
    1 AX=-X
      GO TO 3
    2 AX=X
    3 IF (AX-6.0) 5,4,4
    4 P=1.
      D=0.
      GO TO 6
    5 T=1./(1.0+.2316419*AX)
      D=0.3989423*EXP(-X*X/2.0)
      P = 1.0 - D*T*((((1.330274*T - 1.821256)*T + 1.781478)*T -
     1  0.3565638)*T + 0.3193815)
    6 IF (X) 8,7,7
```

```
      7 P=1.0-P
      8 RETURN
        END

        SUBROUTINE AREAS(X1,Y1,X2,Y2,X3,Y3,X4,Y4,AREA)
C        SUBROUTINE TO CALCULATE AREA OF ARBITRARY QUADRILATERAL,
C        WHERE (X1,Y1) AND X4,Y4) ARE OPPOSITE CORNERS.
C           LOCATE INTERSECTIONS OF DIAGONALS:
        IF (X4-X1-0.001) 20,30,30
     20 IF (X4-X1+0.001) 30,30,25
     25 XX=X1
        A2=(Y3-Y2)/(X3-X2)
        YY=(XX-X3)*A2 +Y3
        DIST1=Y4-Y1
        IF (DIST1) 26,27,27
     26 DIST1=-DIST1
     27 DIST2=SQRT((X3-X2)*(X3-X2) + (Y3-Y2)*(Y3-Y2))
        GO TO 100
     30 IF (X3-X2-0.001) 50,70,70
     50 IF (X3-X2+0.001) 70,70,65
     65 XX=X3
        A1=(Y4-Y1)/(X4-X1)
        YY=(XX-X4)*A1+Y4
        DIST2=Y3-Y2
        IF (DIST2) 66,67,67
     66 DIST2=-DIST2
     67 DIST1=SQRT((X4-X1)*(X4-X1) + (Y4-Y1)*(Y4-Y1))
        GO TO 100
     70 A1=(Y4-Y1)/(X4-X1)
        A2=(Y3-Y2)/(X3-X2)
        XX=(Y2-Y1+A1*X1-A2*X2)/(A1-A2)
        YY=A1*(XX-X1) + Y1
        DIST1=SQRT((X4-X1)*(X4-X1) + (Y4-Y1)*(Y4-Y1))
        DIST2=SQRT((X3-X2)*(X3-X2) + (Y3-Y2)*(Y3-Y2))
C            CALCULATE LENGTH OF SIDES OF SUB-TRIANGLE
    100 SIDE1=SQRT((XX-X1)*(XX-X1) + (YY-Y1)*(YY-Y1))
        SIDE2=SQRT((XX-X2)*(XX-X2) + (YY-Y2)*(YY-Y2))
        SIDE3=SQRT((X1-X2)*(X1-X2) + (Y1-Y2)*(Y1-Y2))
C            SOLUTION ACCORDING TO C.R.C. HANDBOOK UNDER
C                 'MENSURATION FORMULAE' AND 'TRIGONOMETRIC FORMULAE'
        SS=(SIDE1+SIDE2+SIDE3)/2.
        SINANG=2.*SQRT(SS*(SS-SIDE1)*(SS-SIDE2)*(SS-SIDE3))/(SIDE1*SID
        AREA=0.5*DIST1*DIST2*SINANG
        RETURN
        END

        SUBROUTINE CIRCLE(RC,INGS,FRAREA,RSK)
        COMMON NRD,NWR,NLEI,TI(12),RSKTI(12)
        COMMON C1,C2,C3,SIG,RZERO,RONE,AAA,BBB
        COMMON NGS,NRS(10),AM0(11),AM1(11),LORS(11)
        COMMON BETA(11),RATE(11),COEF(11),FDEPTH(11)
        COMMON NSTEPO,NSTEPI,JCALC,JPRNT
        COMMON INDIC(4),AREA(10,11)
        DIMENSION RSK(12)
```

```
C         SUBROUTINE TO CALCULATE RISK FROM A CIRCULAR
C         SOURCE WITH CENTER AR SITE, RADIUS RC.
      NRC=RC
C         CHOOSE STEP SIZE:
C              STEP SIZE = NSTEPI ULESS RESULTING STEP SIZE IS
C              LESS THAN ONE KILOMETRE, IN WHICH CASE RC+1
C              STEPS ARE USED.
      IF (NRC-NSTEPI) 10,12,12
   10 NSTEPX=NRC+1
      GO TO 14
   12 NSTEPX=NSTEPI
   14 ANSTEP=NSTEPX
      DO 90 II=1,NSTEPX
      AI=II
      R=((AI-0.5)*RC)/ANSTEP
      ANAREA=6.2831853072 *R*RC/ANSTEP
      RATEI=RATE(INGS)*ANAREA*FRAREA
      DO 80 JJ=1,NLEI
      IF (JCALC) 50,50,60
   50 CALL RISK1(TI(JJ),R,INGS,RISK)
      GO TO 70
   60 CALL RISK2(TI(JJ),R,INGS,RISK)
   70 RSK(JJ)=RSK(JJ)+RISK*RATEI
   80 CONTINUE
   90 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE INSIDE(XNOT,YNOT,INGS,INSS,XL,YL,XR,YR,AA,BB)
      COMMON NRD,NWR,NLEI,TI(12),RSKTI(12)
      COMMON C1,C2,C3,SIG,RZERO,RONE,AAA,BBB
      COMMON NGS,NRS(10),AM0(11),AM1(11),LORS(11)
      COMMON BETA(11),RATE(11),COEF(11),FDEPTH(11)
      COMMON NSTEPO,NSTEPI,JCALC,JPRNT
      COMMON INDIC(4),AREA(10,11)
      DIMENSION XL(4),YL(4),XR(4),YR(4),AA(4),BB(4),XC(4),YC(4)
      DIMENSION RSK(10)
C         SUBROUTINE FOR CALCULATING RISK WHEN SITE IS INSIDE
C                 SOURCE AREA.
C           REFER TO DOCUMENTATION FOR ALGORITHM USED TO CHOOSE
C                 NUMBER OF INTEGRATION STEPS.
      DO 50 II=1,NLEI
   50 RSK(II)=0.
      APPROX=0.
      RC2=10000000000.
      RF2=0.
C          FIND CLOSEST SIDE AND FARTHEST POINT
      DO 160 II=1,4
      GO TO (120,110),INDIC(II)
  110 XS=XL(II)
      YS=YNOT
      GO TO 140
C          IS SLOPE ZERO?
  120 IF (AA(II)-0.001) 121,125,125
  121 IF (AA(II)+0.001) 125,125,122
```

```
 122  XS=XNOT
      YS=YL(II)
      GO TO 140
C        SLOPE NOT ZERO
 125  XS=(YNOT+(XNOT/AA(II))-BB(II))/(AA(II)+1./AA(II))
      YS=((XNOT-XS)/AA(II))+YNOT
C          CALCULATE SQUARE OF DISTANCE BETWEEN SITE AND CLOSEST POINT.
 140  DIST=(XNOT-XS)*(XNOT-XS)+(YNOT-YS)*(YNOT-YS)
      IF (DIST-RC2) 151,152,152
 151  RC=SQRT(DIST)
      RC2=DIST
      ICLO=II
C          CALCULATE DISTANCE BETWEEN SITE AND LEFT HAND POINT ON SIDE
 152  DIST=(XNOT-XL(II))*(XNOT-XL(II))+(YNOT-YL(II))*(YNOT-YL(II))
      IF (RF2-DIST) 154,160,160
 154  RF=SQRT(DIST)
      RF2=DIST
      IFAR=II
 160  CONTINUE
C          DETERMINE AZIMUTH OF FARTHEST POINT WITH RESPECT TO SITE
      AZIMF=ACOS((XL(IFAR)-XNOT)/RF)
      IF (YL(IFAR)-YNOT) 162,164,164
 162  AZIMF=6.2831853072 - AZIMF
 164  CONTINUE
C      RC IS NOW DISTANCE FROM SITE TO CLOSEST SIDE.
C      RF IS NOW DISTANCE FROM SITE TO FARTHEST CORNER.
      IF (RC-0.01) 200,200,170
C        CALL SUBROUTINE CIRCLE TO CALCULATE RISK FROM CIRCULAR
C            SOURCE WITH RADIUS RC
 170  NTOT=NRS(INGS)+1
      FRAREA=AREA(INGS,INSS)/AREA(INGS,NTOT)
      CALL CIRCLE(RC,INGS,FRAREA,RSK)
      APPROX=3.1415926536*RC*RC
C       LOOP ON R TO CALCULATE RISK FROM RC TO RF
 200  AN=NSTEPI
C        PICK STEP SIZE BASED ON FRACTION OF AREA LEFT
      FRLEFT=(AREA(INGS,INSS)-APPROX)/AREA(INGS,INSS)
      NSTEPX=FRLEFT*AN + 1.
      AN=NSTEPX
      STSIZE=(RF-RC)/AN
      DO 500 ISTEP=1,NSTEPX
      AI=ISTEP
      R=RC+(AI-0.5)*STSIZE
      NPT=0
      ANGLE=0.
C         LOOP ON EACH SIDE
      DO 400 II=1,4
      GO TO (330,320),INDIC(II)
C         SIDE II IS VERTICAL, DOES CIRCLE (RADIUS R) INTERSECT IT?
 320  A=XL(II)-XNOT
      IF (A) 322,322,323
 322  IF (R+A) 400,400,324
 323  IF (R-A) 400,400,324
C         COMPUTE 2 INTERSECTION POINTS
 324  X1=XL(II)
```

```
      B=SQRT(R*R-(X1-XNOT)*(X1-XNOT))
      Y1=YNOT+B
      X2=XL(II)
      Y2=YNOT-B
      GO TO 341
  330 A=1.+AA(II)*AA(II)
      B=2.*(-XNOT+AA(II)*(BB(II)-YNOT))
      C=XNOT*XNOT+YNOT*YNOT+BB(II)*(BB(II)-2.*YNOT)-R*R
      D=B*B-4.*A*C
      IF (D) 400,400,340
C          THERE ARE 2 INTERSECTION, CALCULATE THEIR COORDINATES.
  340 D=SQRT(D)
      X1=(-B+D)/(2.*A)
      Y1=AA(II)*X1+BB(II)
      X2=(-B-D)/(2.*A)
      Y2=AA(II)*X2+BB(II)
C          SEE IF (X1,Y1) IS ON BOUNDARY
  341 CALL BETWEN(XL(II),YL(II),XR(II),YR(II),X1,Y1,INDIC(II),IANS)
      IF (IANS) 350,342,345
  342 NERROR=4
      GO TO 800
C       IS SECOND POINT ALSO ON BOUNDARY?
  345 CALL BETWEN(XL(II),YL(II),XR(II),YR(II),X2,Y2,INDIC(II),IANS)
      IF (IANS) 348,346,360
  346 NERROR=5
      GO TO 800
C         STORE FIRST POINT ONLY
  348 NPT=NPT+1
      XC(NPT)=X1
      YC(NPT)=Y1
      GO TO 400
C        SEE IF SECOND POINT ONLY IS ON BOUNDARY
  350 CALL BETWEN(XL(II),YL(II),XR(II),YR(II),X2,Y2,INDIC(II),IANS)
      IF (IANS) 400,352,354
  352 NERROR=6
      GO TO 800
  354 NPT=NPT+1
      XC(NPT)=X2
      YC(NPT)=Y2
      GO TO 400
C         TWO INTERSECTION POINTS ON ONE SIDE BOTH LIE ON BOUNDARY,
C          CALCULATE ANGLE BETWEEN THEM.
  360 CONTINUE
  380 AD=SQRT((X1-X2)*(X1-X2)+(Y1-Y2)*(Y1-Y2))
      ANGLE=2.*ASIN(AD/(2.*R))+ANGLE
  400 CONTINUE
      IF (NPT) 402,404,408
  402 NERROR=7
      GO TO 800
  404 IF (ANGLE-0.001) 402,406,406
C        FOLLOWING IS FOR CASE OF NO SINGLE INTERSECTION POINTS;
C        ANGLE IS 2 * PI - ANGLE CALCULATED SO FAR.
  406 PANGLE=6.2831853072-ANGLE
      GO TO 460
  408 GO TO (402,410,402,440),NPT
```

```
      NERROR=8
      GO TO 800
C         2 INTERSECTION POINTS; DETERMINE AZIMUTHS.
  410 IF (XC(1)-XNOT-R) 414,413,411
  411 IF (XC(1)-XNOT-R-0.001) 413,413,412
  412 NERROR=18
      GO TO 800
  413 AZIM1=0.0
      GO TO 418
  414 IF (XC(1)-XNOT+R) 415,416,417
  415 IF (XC(1)-XNOT+R+0.001) 412,416,416
  416 AZIM1=3.1415926536
      GO TO 420
  417 AZIM1=ACOS((XC(1)-XNOT)/R)
  418 IF (YC(1)-YNOT) 419,420,420
  419 AZIM1=6.2831853072  - AZIM1
  420 IF (XC(2)-XNOT-R) 424,423,421
  421 IF (XC(2)-XNOT-R-0.001) 423,423,422
  422 NERROR=19
      GO TO 800
  423 AZIM2=0.0
      GO TO 428
  424 IF (XC(2)-XNOT+R) 425,426,427
  425 IF (XC(2)-XNOT+R+0.001) 422,426,426
  426 AZIM2=3.1415926536
      GO TO 430
  427 AZIM2=ACOS((XC(2)-XNOT)/R)
  428 IF (YC(2)-YNOT) 429,430,430
  429 AZIM2=6.2831853072 -AZIM2
  430 PANGLE=AZIM2-AZIM1
      IF (PANGLE) 431,439,435
  431 IF (AZIM1-AZIMF) 432,439,433
  432 PANGLE=6.2831853072 +PANGLE -ANGLE
      GO TO 460
  433 IF (AZIMF-AZIM2) 432,439,434
  434 PANGLE=-PANGLE-ANGLE
      GO TO 460
  435 IF (AZIM2-AZIMF) 436,439,437
  436 PANGLE=6.2831853072 -PANGLE -ANGLE
      GO TO 460
  437 IF (AZIMF-AZIM1) 436,439,438
  438 PANGLE=PANGLE-ANGLE
      GO TO 460
  439 NERROR=9
      GO TO 800
C        FOUR INTERSECTION POINTS (EACH ON A DIFFERENT SIDE).
C        DETERMINE ANGLE BY FINDING CLOSEST 2 INTERSECTIONS TO
C        FARTHEST CORNER, CALCULATE ANGLE BETWEN, AND ADD ANGLE
C        BETWEEN OTHER TWO INTERSECTIONS.
  440 DIST1=1000000000.
      I1=0
      I2=0
      I3=0
      I4=0
      DO 450 JJ=1,4
```

```
      DIST=(XL(IFAR)-XC(JJ))*(XL(IFAR)-XC(JJ))
     1   +(YL(IFAR)-YC(JJ))*(YL(IFAR)-YC(JJ))
      IF (DIST-DIST1) 442,444,444
 442  DIST2=DIST1
      DIST1=DIST
      I4=I3
      I3=I2
      I2=I1
      I1=JJ
      GO TO 450
 444  IF (DIST-DIST2) 445,446,446
 445  DIST2=DIST
      I4=I3
      I3=I2
      I2=JJ
      GO TO 450
 446  I4=I3
      I3=JJ
 450  CONTINUE
C        CALCULATE ANGLE BETWEEN 2 CLOSEST POINTS TO FARTHEST CORNER
      AD=SQRT((XC(I1)-XC(I2))*(XC(I1)-XC(I2))
     1 + (YC(I1)-YC(I2))*(YC(I1)-YC(I2)))
      PANGLE=2.*ASIN(AD/(2.*R))
C         CALCULATE ANGLE BETWEEN 2 FARTHEST POINTS FROM
C         FARTHEST CORNER AND ADD TO PREVIOUS ANGLE.
      AD=SQRT((XC(I3)-XC(I4))*(XC(I3)-XC(I4))
     1 + (YC(I3)-YC(I4))*(YC(I3)-YC(I4)))
      PANGLE=2.*ASIN(AD/(2.*R))+PANGLE
C       ANGLE FOR THIS RADIUS IS NOW KNOWN, CALCULATE RISK
 460  CONTINUE
      ANAREA=PANGLE*R*STSIZE
      APPROX=APPROX+ANAREA
      NTOT=NRS(INGS)+1
      RATEI=RATE(INGS)*ANAREA*AREA(INGS,INSS)/AREA(INGS,NTOT)
C       CALCULATE CONTRIBUTION TO RISK
      DO 480 JJ=1,NLEI
      IF (JCALC) 470,470,475
 470  CALL RISK1(TI(JJ),R,INGS,RISK)
      GO TO 478
 475  CALL RISK2(TI(JJ),R,INGS,RISK)
 478  IF (RISK-0.0000000001) 500,490,490
 490  RSK(JJ)=RSK(JJ) +RISK*RATEI
 480  CONTINUE
 500  CONTINUE
      ARERR=((APPROX-AREA(INGS,INSS))/AREA(INGS,INSS))*100.
      IF (ARERR-5.) 510,520,520
 510  IF (ARERR+5.) 520,520,540
 520  WRITE (NWR,903) ARERR,INGS,INSS
 903  FORMAT(10X,'CAUTION: NUMERICAL INTEGRATION ERROR IN AREA IS ',
     1 F6.2,' % FOR (INSIDE) SOURCE ',2I3)
 540  DO 550 JJ=1,NLEI
      RSK(JJ)=COEF(INGS)*RSK(JJ)/APPROX
 550  RSKTI(JJ)=RSKTI(JJ)+RSK(JJ)
      IF (JPRNT) 850,850,610
C         PRINT RISKS FOR THIS SOURCE.
```

```
  610 WRITE(NWR,902) INGS,INSS,(RSK(I),I=1,NLEI)
  902 FORMAT(' SOURCE',2I3,' E(NO/YR): ',12E9.3)
      GO TO 850
C          ERROR PRINTOUT
  800 WRITE (NWR,901) NERROR,INGS,INSS,IF,NPT,XNOT,YNOT,(XL(I),YL(I),
     1 I=1,4),RC,RF,R,PANGLE,(XC(I),YC(I),I=1,4)
  901 FORMAT (' ***** ERROR',I4,' IN SUBROUTINE INSIDE. SOURCE NO.',
     1 2I3,' DEBUG VALUES FOLLOW......',/10X,2I10,10(/10X,2F12.6))
  850 RETURN
      END
```