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FRISK: Computer Program For Seismic Risk Analysis Using Faults as Earthquake Sources

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FRISK: COMPUTER PROGRAM FOR SEISMIC RISK ANALYSIS USING FAULTS AS EARTHQUAKE SOURCES

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ABSTRACT

This computer program makes probabilistic seismic hazard calculations at sites affected by earthquakes occurring on faults which are defined by the user as a series of line segments. The length of rupture of the fault as a function of earthquake magnitude is accounted for, and ground motion estimates at the site are made using the magnitude of the earthquake and the closest distance from the site to the rupture zone. Uncertainty in the earthquake magnitude, in the rupture given magnitude, in the location of the rupture zone on the fault, in the maximum possible magnitude of earthquakes, and in the ground motion at the site given the earthquake, its size, rupture length, and location, are accounted for explicitly. FRISK (Fault RISK) was written to take advantage of repeated calculations, so that seismic hazard analyses for several ground motion parameters (for instance, peak ground acceleration, velocity, and displacement), and for several sites, are most efficiently made with one execution of the program rather than with repeated executions.

The program uses a step-truncated exponential distribution for earthquake magnitude, a lognormal distribution for rupture length given magnitude, a uniform distribution for rupture location on faults, and a lognormal distribution of site amplitude given magnitude of the earthquake and distance from the rupture zone to the site. The program has been structured so that other functions may easily be substituted if this is appropriate for a particular problem; for example a wide range of deterministic or probabilistic geophysical models for estimating ground motion may be incorporated, and the program will yield probabilistic estimates of seismic hazard.

INTRODUCTION

Since the advent of seismic risk analysis methods a decade ago, much work has been done both in applying these methods to engineering problems and in revising these methods to reflect more refined information and theories about seismicity, wave propogation, and the features of seismic ground motion which are critical to engineering structures. One important advance was recognition that the length of fault rupture during an earthquake is an important consideration in probabilistic calculations of seismic hazard.

The computer program described in this document calculates seismic hazard for problems in which the length of fault rupture during an earthquake must be accounted for. Important uncertainties are included in the calculations: uncertainties in the magnitudes of future earthquakes, in the rupture length given magnitude, in the maximum possible magnitude on a fault, and in the seismic ground motion at the site of interest given the earthquake, its rupture length, and its location on the fault.

The program currently uses typical analytical functions to describe seismicity and ground motion propagation from source to site. Coding for the program and the documentation included herein have been written in a manner which will allow easy incorporation of new analytical or empirical functions when these become available, without major reprogramming. The program, as currently written, is not meant to be the final word in seismic risk analysis; it is a tool which can be revised and refined to reflect advances in the state of the art.

In any major programming effort such as this one, there are bound to be errors in coding and in documentation. The experience of users, and the notification of any discovered errors, will be gratefully received by the author. A form is provided at the back of this document to include users' names on a mailing list for notification of changes in the program which correct errors or increase its versatility.

THEORETICAL BACKGROUND

Methods of probabilistic seismic hazard analysis have been developed and documented over the past decade (for instance, see Cornell, 1968, 1971; McGuire, 1974, 1976; Der Kiureghian and Ang, 1975, 1977). A brief description of the method used by program FRISK is given, along with the explicit and implicit assumptions. The assumptions which can easily be changed, and the re-programming necessary to effect these changes, are also described.

Throughout this documentation, the term "fault" refers to a defined zone in the earth's crust which may be the source of future earthquakes; the term "rupture" refers to the section of a fault which breaks during a specific earthquake. Faults are defined by a series of connected line segments, and earthquakes occur at random locations on these faults. The locations, sizes, and other parameters of successive earthquakes are mutually independent.

The program calculates the probability that a specific ground motion amplitude will be exceeded at the site by a numerical evaluation of the "Total Probability Theorem." (The term "amplitude" here means any quantitative ground motion measure which can be described within the assumptions of the methodology, for instance peak ground acceleration or velocity, spectral velocity, and so on. Modified Mecalli intensity may also be used with certain variations to the input as discussed below. Specifically, the probability that amplitude is exceeded given one event (of random size, rupture length, and location) on a fault, is

$$P[\text{amplitude } z \text{ exceeded}]$$

$$= \iiint P[\text{amplitude } z \text{ exceeded} \mid m, l_r(m), x] \; f_M(m)\; f_L(l_r)\; f_X(x) \;\; dm\; dl_r\; dx \qquad (1)$$

where M is magnitude, L_r is length of rupture, and X indicates rupture location on the fault. Given the location and length of rupture, the closest distance from the rupture to the site is calculated, and the probability in the integrand is evaluated. Integration over M, L_r, and X gives the total probability that amplitude z will be exceeded due to a single event of random M, L_r and X. To calculate the expected number of exceedances, this probability is multiplied by the mean activity rate for the time of interest. The total expected number of exceedances is calculated as the sum of expected numbers from each fault, and the risk at the site for amplitude z (that is, the probability that z is exceeded) under the Poisson assumption is determined by

$$\text{Risk (amplitude } z) = 1 - \exp(-\text{total expected number of exceedences of amplitude } z) \qquad (2)$$

Ground motion amplitudes associated with specified levels of risk are determined by interpolation using the calculated risks which are next higher and next lower, and using the associated amplitudes. This interpolation is made logarithmically for both amplitudes and risks, because risks usually decrease almost linearly with amplitude when plotted on full logarithmic paper.

The specific functions used in the program for the magnitude, rupture length, and location distributions, and for the distribution of ground motion amplitude given earthquake magnitude and closest distance from the site to the rupture, are discussed below. These distributions may easily be changed if other functions are more appropriate for a specific case.

The magnitude distribution for earthquakes on each fault is modeled by a truncated exponential distribution that is:

$$f_M(m)=k\beta \exp(-\beta(m-m_o)) \qquad m_o \leq M \leq M_1 \qquad (3)$$

where f_M is the magnitude density function, m is the magnitude of the earthquake, m_o and M_1 are lower and upper bounds, β is the slope parameter (equal to ln 10 times the Richter b value), and k is equal to $(1-\exp(-(M_1-m_o)))^{-1}$. The upper bound magnitude M_1 may be given a deterministic value or a discrete distribution (that is, a set of values with associated probabilities). A magnitude distribution other than the truncated exponential is easily incorporated in the program; since integration over magnitude is done numerically in the program, it is necessary only to calculate with the desired distribution the probability that earthquakes occur with sizes in a defined magnitude range. The location in the program for making this change is indicated with comment cards.

The rupture length of an earthquake is uncertain; the distribution of rupture length is taken to be lognormal, with parameters a function of the magnitude of the event. The mean value of the logarithm of rupture length l_r is assumed to be a linear function of magnitude:

$$\text{mean } \log_{10} l_r = a_1 + b_1 m \qquad (4)$$

where a_1 and b_1 are constants. This mean value, and the standard deviation $\sigma_{\log_{10} l_r}$, are sufficient to define the rupture length distribution for magnitude m. As is the case with the magnitude distribution, alternate distributions may be used for rupture length. The appropriate place to make changes to incorporate a different rupture length distribuiton is indicated with comment cards in the program.

The location of the rupture length is assumed to be equally likely any place on the fault. Computationally, the energy center is defined as the point on the rupture equidistant from the two end points, and its location is assumed to be uniformly distributed any place on the fault except within $l_r/2$ of the ends. This last restriction ensures that the earthquake cannot rupture past the end of the fault. It is possible to introduce alternate assumptions on rupture location but it may be easier and more appropriate to divide a single fault into several faults with different activity rates. Note, however, that one long fault cannot be represented exactly as several faults laid end-to-end, because earthquakes are not allowed to rupture past the end of any fault.

A myriad of assumptions are possible regarding the temporal process governing earthquake occurrences, with the program as currently written. The form of the input and output is the same, but their interpretations are different. For example, if it is assumed that earthquakes occur as a Poisson process, mean activity rates for each fault are input, and the program outputs both the expected number of times that amplitude levels of interest will be exceeded (consistent with the time period used for activity rates) and the risk associated with these amplitude levels (that is, the probability that they will be exceeded).

Alternately, if any of a wide range of recurrence processes is assumed, the mean rate of occurrence is again input, and the program again computes the expected number of times selected amplitude levels will be exceeded. In this case the total expected number is an estimate of the risk, but is a conservative and generally accurate estimate (as explained below). Finally, in the most general application, if one chooses not to assume any temporal process at all, one inputs (in place of the activity rate for each fault), the probability that an event occurs on that fault during the time of interest. If this number is low (as is generally the case), the probability of multiple events is negligible, and the "Expected Numbers" output by the program are in fact probabilities that the selected amplitudes will be exceeded by earthquakes on a single fault; the "Total Expected Numbers" are conservative and generally accurate estimates of the risk for the amplitudes of concern, for earthquakes on all faults. This last statement follows from the fact that, if p_i is the probability that an earthquake occurs on fault i and causes some amplitude level at the site to be exceeded, then

$$\sum_i p_i \gtrsim 1 - \prod^{i} (1-p_i) \qquad (5)$$

The expression on the right is an exact calculation of risk from all faults; the summation of probabilities on the left is an accurate estimate of the risk if the total risk is less than about 0.3. This is usually the case for seismic hazard problems; that is, the amplitudes of interest generally have an associated risk less than 0.3 for the time period of interest.

The ground motion amplitude measure Z is assumed to be lognormally distributed; parameters of the distribution are a function of source size and distance. The expected value of the logarithm of Z is given by

$$E(\ln Z)=c_1+c_2M+c_3 \ln (R + r_o) \qquad (6)$$

where Z is the amplitude of interest (peak ground acceleration, spectral velocity, etc.), M is magnitude, R is distance from the site to the closest point of rupture, and c_1 c_2 c_3, and r_o are constants. Uncertainty in ln Z is assumed to be normally distributed, with standard deviation $\sigma_{\ln Z}$.

As alternatives to this attenuation function, it is possible to introduce a variety of models to estimate ground motion at the site. At the appropriate place in the program (during integration of equation 1 above), the location of the rupture on the fault is given with respect to the site. A ground motion model which accounts for (for instance) azimuthal and focusing effects as well as source size and distance could easily be introduced. Even a deterministic ground motion function could be introduced; the program would yield probabilistic estimates of ground motion through integraton over uncertainties in magnitude, rupture length, and location.

FRISK can be used to calculate probabilites that selected values of Modified Mercalli intensity I_s will be exceeded at a site. In this case the seismicity of a region is typically described using the maximum Modified Mercalli intensity at the epicenter I_e to indicate earthquake size, and specifying the activity rate, β, maximum possible size, and rupture length in terms of I_e. The applicable attenuation function is

$$E(I_s) = c_1 + c_2 I_e + c_3 \ln(R + r_o) \qquad (7)$$

and the specified standard deviation σ_{I_s} is used with a normal distribution. In calculating probabilities using Modified Mercalli intensity with the current version of FRISK, intensities are considered a continuous, not a discrete, variable. Thus the user should take care whether, for example, Modified Mercalli intensity V is correctly represented on the continuous scale as 5.0 or 5.5. When specifying amplitudes for which risks are to be calculated (on card 5 described in the section entitled "Required Input"), the user should input the quantity $\exp(I_s)$, because the program takes logarithms of the specified amplitudes to calculate probabilities using attenuation equation (6) or (7).

PROGRAM OPERATION AND OPTIONS

The program calculates risk according to equation 1 with a series of nested "DO" loops. Operation of the program is shown in figure 1 in an overall sense. The loop on "Problems" allows calculation of risk for several ground motion parameters simultaneously (for instance, peak ground acceleration and displacement). The loop on sites is inside the loops on fault, magnitude, rupture length, and energy center location, so that calculations required to locate a certain rupture on the fault and determine the associated probabilities are made only once for all sites. A result of this efficiency in operation is that calculated risks for each site must be stored (in array "RISK" which has four dimensions) until all calculations are finished.

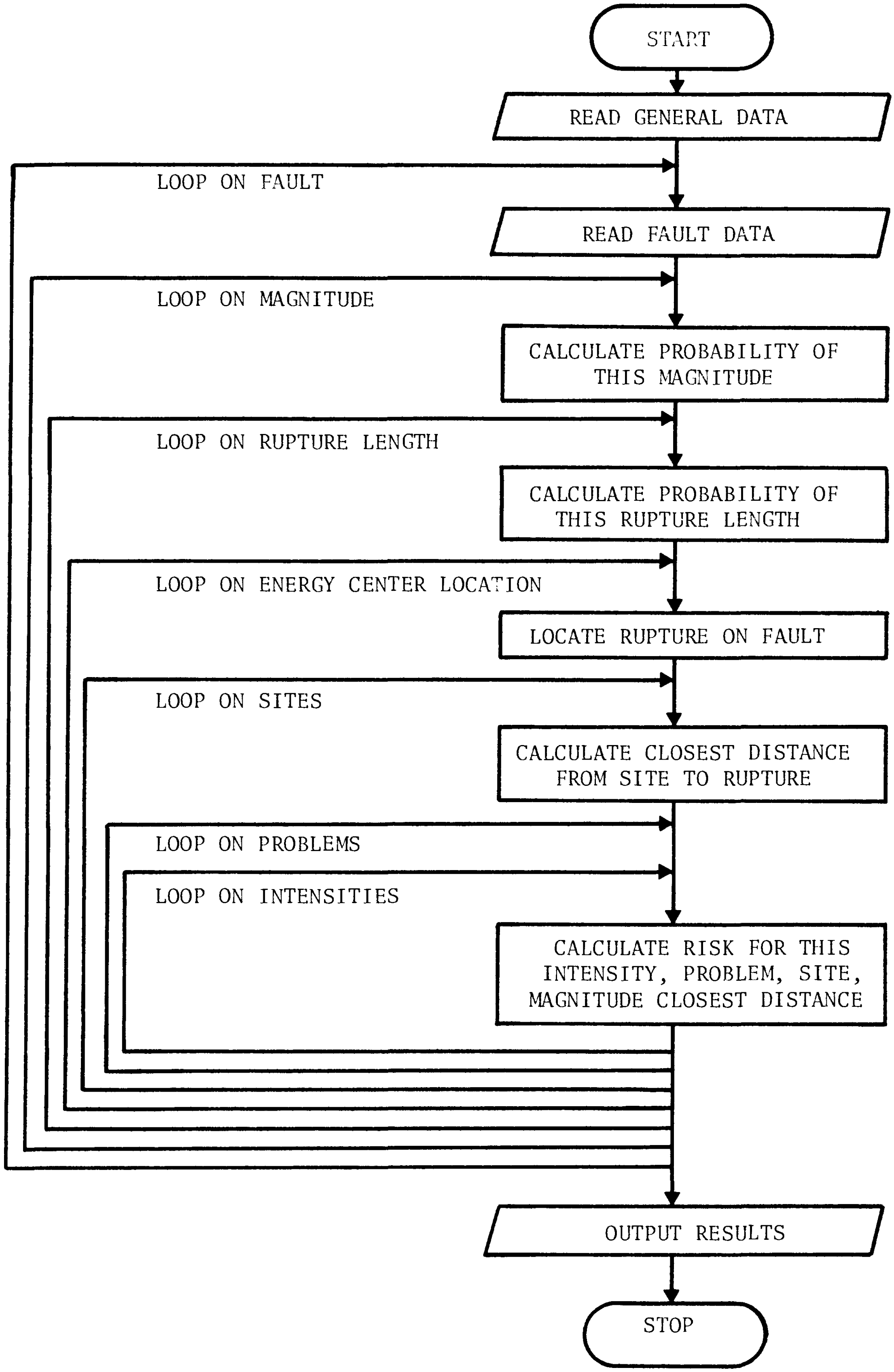


Figure 1.--Macro flowchart of program.

Changes to incorporate a more sophisticated ground motion model than that currently adopted in the program (which uses only magnitude and closest distance to rupture as the controlling variables), are easily accomplished. Within the loop on sites, the location of the rupture on the fault is defined as a series of line segments (the number of which is contained in variable NSRL) with end point coordinates contained in arrays RLX and RLY, from elements 1 through NSRL+1. The site under consideration is located at SITEX(2,JK) and SITEY(2,JK). A visual example is given in figure 2. Site and rupture locations are given in a Cartesian coordinate system; this is the user's system if Cartesian locations were input, and it is a system with origin at the average latitude and longitude of all sites if latitudes and longitudes were used to identify site and fault locations by the user. With the location of the rupture thus defined, virtually any mathematical ground motion model for strike-slip or other faulting can be used to estimate ground motion at the site. Once this model is implemented, the program will integrate over rupture location, rupture length, and magnitude to yield a probabilistic estimate of the ground motion measure of interest.

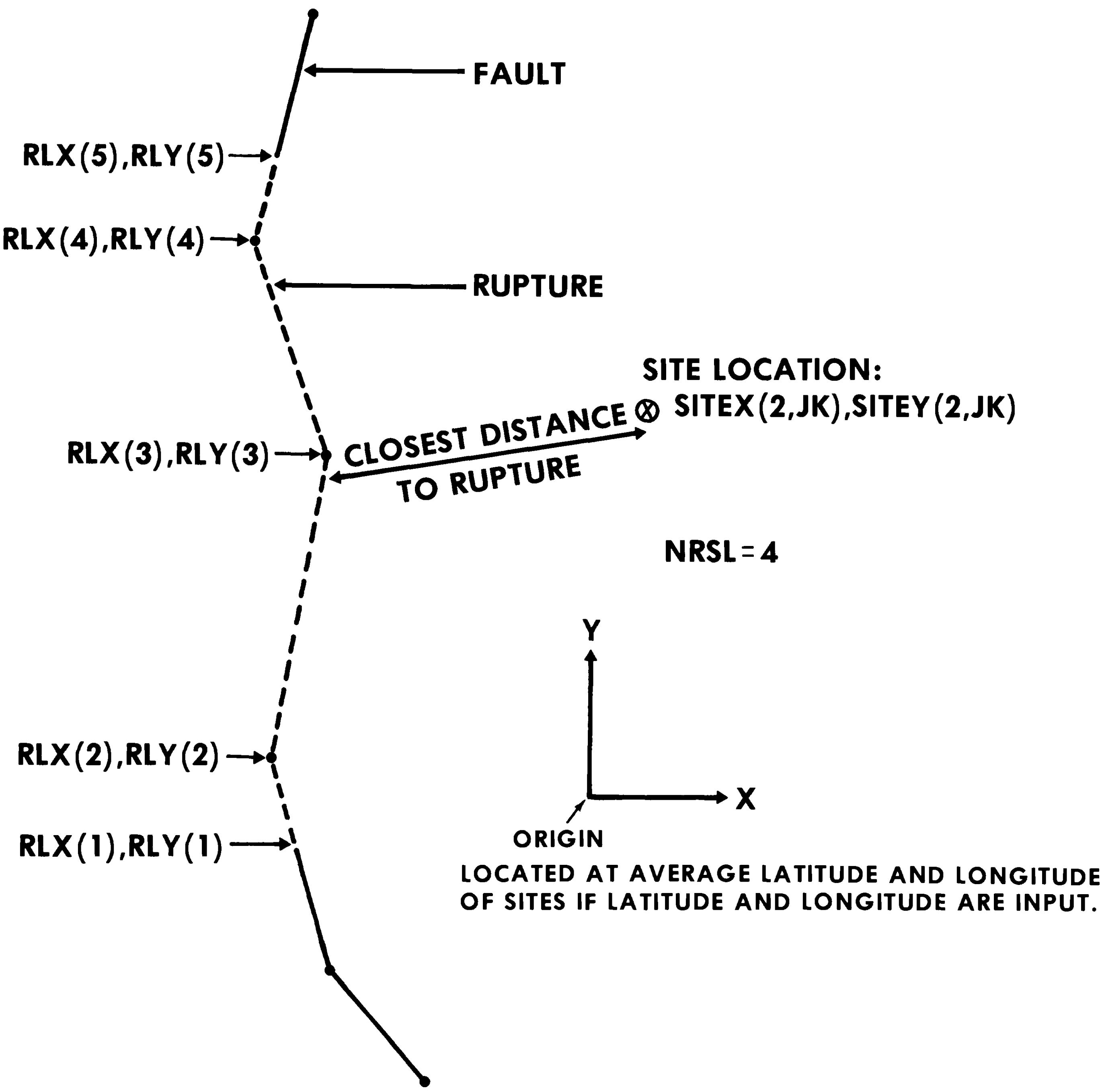


Figure 2.--Typical site and rupture location showing meaning of program variables.

If the risk from a normal or reverse fault were to be calculated, this could be accomplished by changing the program to allow specification of the dip angle (and directon of dip) of the fault. Using the fault line segments to represent the surface expression of faulting, the closest distance to the rupture surface, or any other geometrical variables, could then be computed and used to estimate ground motion at the site; the program would, as usual, integrate over earthquake size and location to calculate seismic hazard.

For a given magnitude the program integrates over possible rupture lengths using equation (3) to determine the mean logarithm of rupture length and assuming a lognormal distribution with standard deviation specified by the user. Computationally, integration is done over the logarithm of rupture length; in general the integration is from the mean value minus two standard deviations, to the mean value plus two standard deviations of $\log_{10} l_r$. When the latter value exceeds the total length of the fault, a truncated lognormal distribution is used, and integration is done from the lower value up to the total fault length. When the mean value minus two standard deviations exceeds the fault length, a warning message is printed and all earthquakes of that magnitude are assumed to rupture the entire fault with probability unity.

As noted in the input documentation, as many as five attenuation equations can be input, and risks can be calculated simultaneously for as many as five ground motion measures. These features can be used in several ways. For instance, two attenuation equations (possibly representing peak ground acceleration and peak ground velocity) can be specified, and the program will compute risks for specific values of acceleration and velocity. Alternately, two or more attenuation equations can be input, one for a set of faults and the others for the remaining faults, and risks will be calculated for one ground motion variable using the appropriate attenuation equation for each fault. Combinations of the above applications are also possible. A third use is to specify one attenuation equation and several "problems;" this allows calculation of risk for many amplitude levels. The maximum number of amplitude levels per problem is ten, which results from the standard width of a line printer page.

The program allows input of the maximum possible magnitude M_1 for each fault as a variable with an associated discrete distribution, rather than as a point estimate. Thus the user can account for statistical or professional uncertainty in this variable. (See, for example, McGuire, 1977.) The risk calculated by the program is virtually the same as the weighted risk which would be calculated at a site from a series of faults all identical except for M_1, with the risk from each fault weighted by the probability associated with its M_1. (To be theoretically correct, the second approach should be followed. The method used here, replacing a point estimate of M_1, by a Bayesian or predictive distribution, gives accurate estimates for risks less than about 0.1, when the calculation of risk can be made by multiplying the probability of exceedance from one event by the mean activity rate. The advantage in using a Bayesian distribution for M_1 is efficiency; integration over magnitude is done only once.)

When a distribution for M_1 is specified, the density function and complementary cumulative function for magnitude are:

$$f_M(m) = \beta \exp(-\beta(m-m_o)) \sum_j p_j k_j \quad (8)$$

$$G_M(m) = 1-[1-\exp(-\beta(m-m_o))] \sum_j p_j k_j \quad (9)$$

where p_j is the probability associated with maximum magnitude M_{1j} when m is between m_o and M_{1j} (p_j is zero otherwise), k_j is $(1-\exp(-\beta(M_{1j}-m_o)))^{-1}$, and other variables are as previously defined. The density function and complementary cumulative function are plotted on figures 3 and 4 for the case where m_o=5.0, β =2.0, and M_1 is assigned values of 7.0 and 8.0 with equal weights (probability 0.5). This "step-truncated exponential distribution" is compared to the "truncated exponential distribution" obtained if either magnitude 7.0 or 8.0 is selected as a deterministic upper bound.

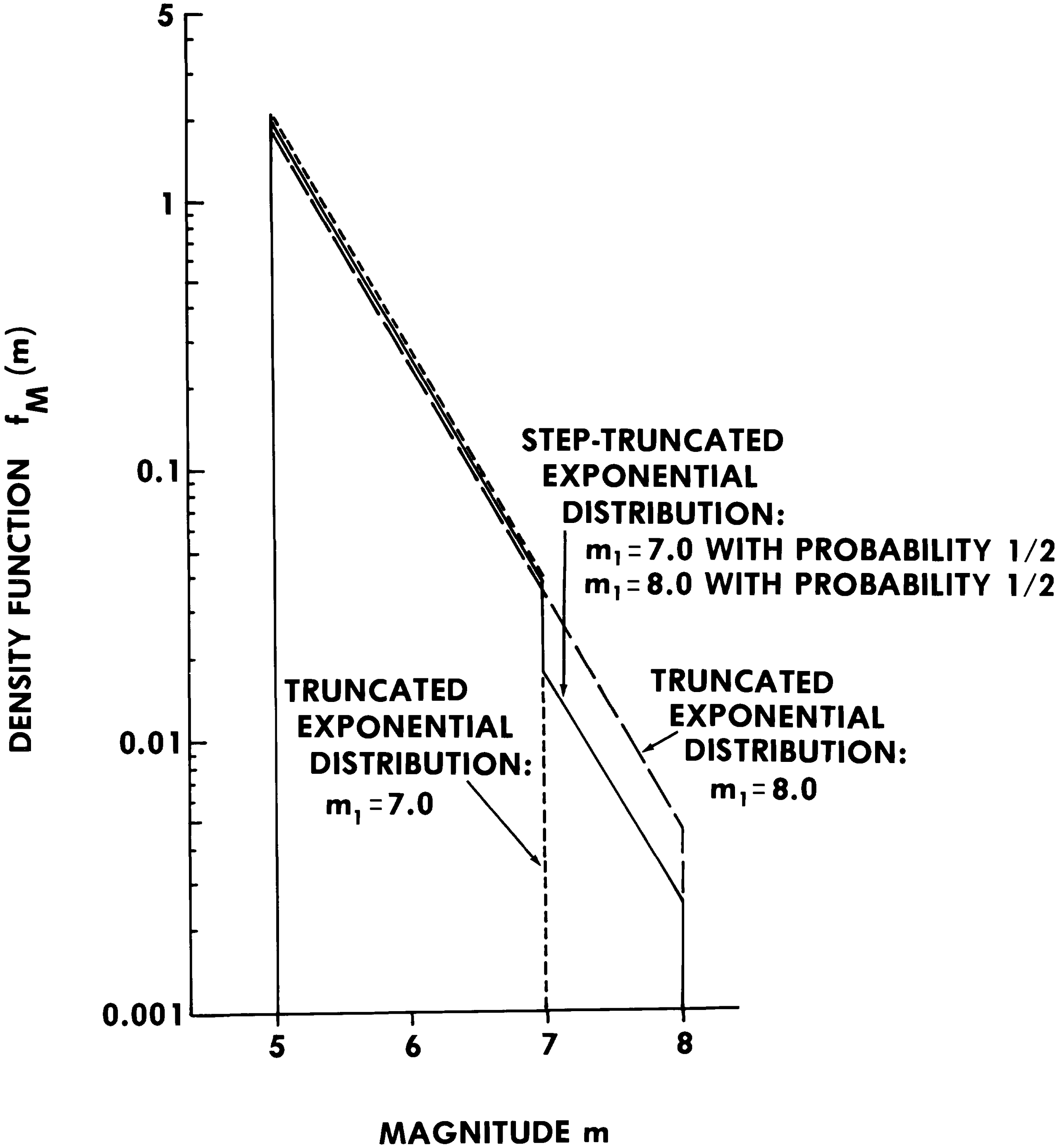


Figure 3.--Density functions for truncated and step-truncated exponential distributions.

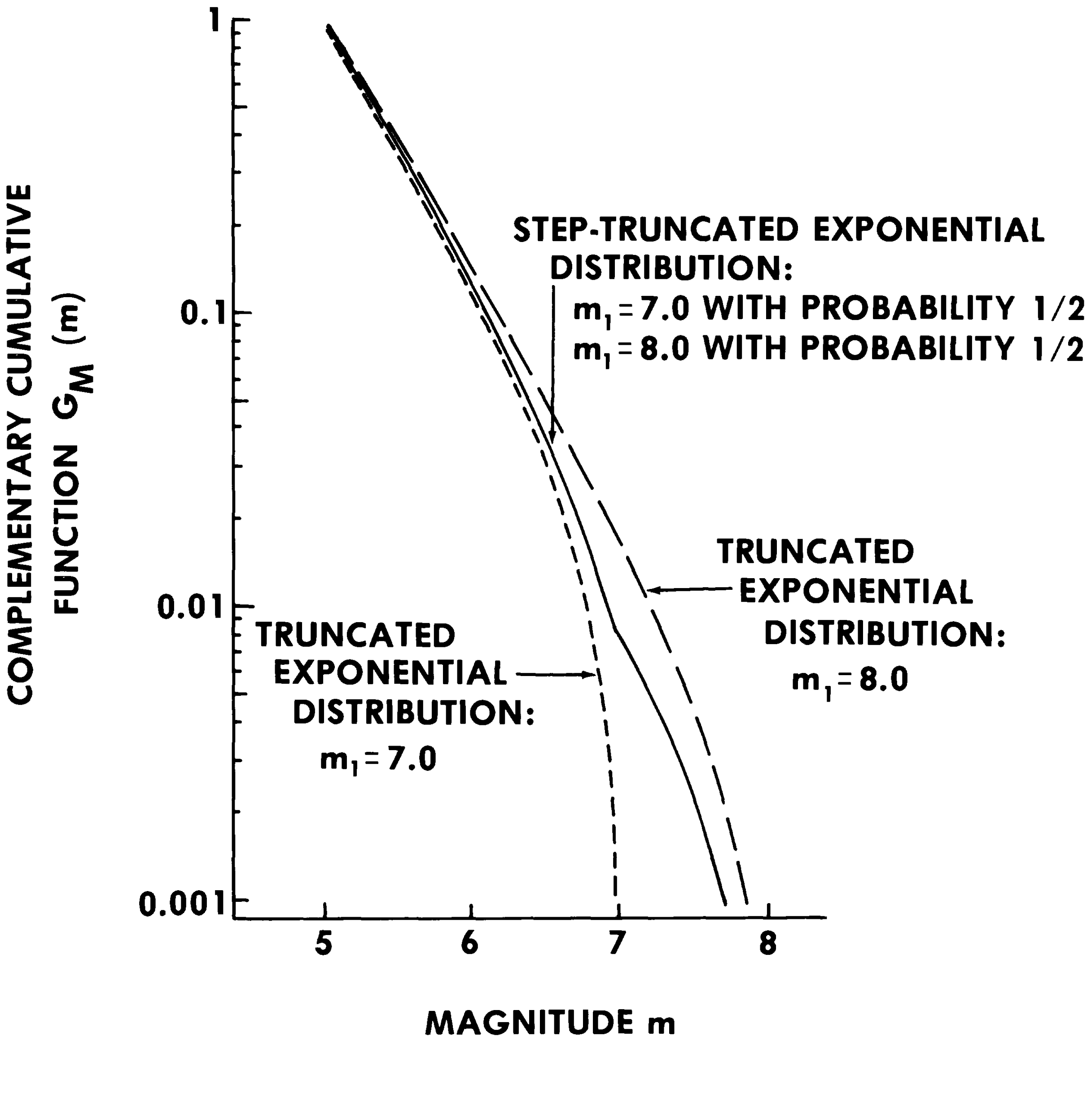


Figure 4.--Complementary cumulative functions for truncated and step-truncated exponential distributions.

REQUIRED INPUT

Input required for operation of program FRISK is described in this section along with limits on the variables, if any:

CARD 1, FORMAT (20A4). TITLE

This card offers a convenient method of describing the individual seismic risk case being addressed. This title will be printed on the data listing, and on the program output listing. Any 80 characters may be used for this description.

CARD 2, FORMAT (5I3). NFLT, NSITE, NPROB, NATT, LCD.

NFLT	indicates the number of faults. It must be between 1 and 10.
NSITE	is the number of grids of sites at which risks are to be calculated (see card 7 below for further explanation). The total number of sites (either generated by grids or individually specified) cannot exceed 50 unless dimension statements in the program are changed.

NPROB is the number of ground motion variables for which risks are to be calculated at each site. For example, risks may be calculated for ground acceleration, velocity, and displacement simultaneously with one execution of this program. This variable must be between 1 and 5.

NATT is the number of attenuation functions used in the study. Ordinarily NATT will be greater than or equal to NPROB. In any case, NATT must be between 1 and 5.

LCD indicates whether site and fault coordinates will be input in longitude-latitude (LCD=1) or in an x-y cartesian system (LCD=2). If a longitude-latitude system is used, the program calculates site and fault locations in a cartesian system with the average latitude and longitude of the sites as the origin, assuming a locally flat earth. Units used for the generated cartesian system are kilometers, so if LCD=1, the attenuation functions, rupture length-magnitude relations, and source depths, <u>must use kilometers as the distance measure.</u>

There must be NATT of the following cards:

CARD 3, FORMAT (5F6.3). C1, C2, C3, RZERO, SIGA.

These variables are parameters in the attenuation function:

$$\ln(z)=C1 + C2*M + C3*\ln(\sqrt{\Delta^2 + h^2} + RZERO)$$

where z is the ground motion amplitude of interest, M is magnitude, Δ is epicentral distance, and h is source depth. SIGA is the standard deviation of this estimation (that is, the standard deviation of ln(z)). If no dispersion is desired, set SIGA to a small number (for example, 0.01) rather than exactly zero.

Cards 4 and 5 form a set; there must be NPROB of these sets:

CARD 4, FORMAT (4A4). DESC.

This card offers the user an opportunity to distinguish among various attenuation equations by labeling them with a 16 character description such as "acceleration" or "velocity." A blank card is required if the user does not wish to use this device.

CARD 5, FORMAT (I3, 3X,10F6.3). NLEI, ATI(1), ATI(2),..ATI(NLEI).

NLEI — indicates the number of ground motion amplitudes (for example, acceleration values) to be studied in this problem. This variable must be between 1 and 10.

ATI(1),... ATI(NLEI) — are amplitudes for which expected numbers and risks are calculated at each site. Input values should be, for example, accelerations or velocities, not the logarithms of these quantities. They must be specified in <u>increasing</u> order. If Modified Mercalli intensities are used, the values of ATI must be exponents of intensities, as discussed elsewhere in this documentation.

CARD 6, FORMAT (I3, 3X, 10F6.3). NRSKD, RISKD(1),...RISKD(NRSKD)

NRSKD — indicates the number of risks for which the corresponding amplitudes are desired, and

RISKD(1),...

RISKD(NRSKD) — are the risks. These may be specified in any order. The program calculates amplitudes for each value of RISKD by interpolation from the risks calculated for the input values of ATI; interpolation is done on a logarithmic scale for both risk and intensity. No extrapolation is made for risks outside the range of risks calculated for the amplitudes in ATI. Therefore, if asterisks are obtained for an input value of RISKD(i), the program must be re-run with a wider range of values specified for array ATI (card 5), to obtain the amplitudes corresponding to that RISKD(i).

There must be NSITE of the following cards:

CARD 7, FORMAT (2F6.3,2I3,2F6.3). SX,SY,NX,NY,DX,DY.

SX,SY — are the X and Y coordinates for the site location. They must be in longitude/latitude or Cartesian form according to the value input for variable LCD on card 2.

NX,NY — indicate the grid size (number of grid points) in the X (longitude) and Y (latitude) directions, for the site grid. If a grid of sites is not desired, NX and NY should be 0 or 1; in this case risk calculations will be made at only a single site located at SX, SY.

DX,DY — indicate the spacing between grid points in the X and Y directions. If no grid is desired, values for these variables may be left blank.

Figure 5 gives a visual explanation of how these variables are used. The total number of sites (that is, number of grid points if a grid is used) cannot exceed 50 without changing dimension statements in the program. Note that in the Western hemisphere longitudes increase to the west, so a specified grid will be generated to the north and west from a site located at SX, SY north of the equator.

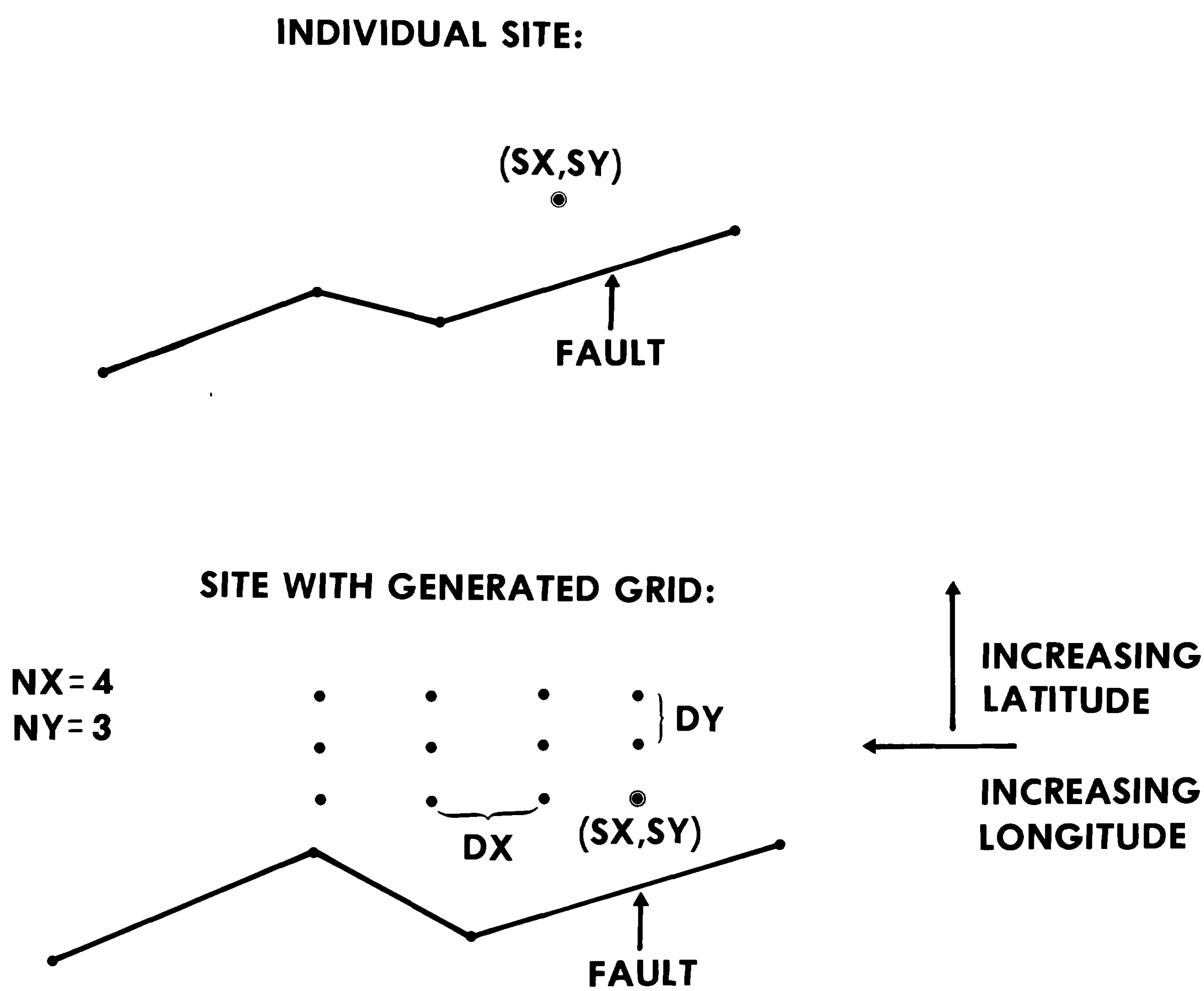


Figure 5.--Examples of site data input on card 7.

Cards 8 through 12 form a set; there must be NFLT of these sets.

CARD 8, FORMAT (12I3). NFP, NRL, IACD(1)...IACD(NPROB).

NFP	is the number of points which define this fault as a series of straight line segments. NFP must be between 2 and 20.
NRL	is the number of steps to be used in the numerical integration over rupture length. The program integrates from the mean minus 2 standard deviations to the mean plus 2 standard deviations of log 10 (rupture length) dividing this interval into NRL steps. If no dispersion in the rupture length-magnitude relation is desired (that is, SIGL is set to a small number on card 11), NRL should be specified as 1. Otherwise, a larger value (typically 4) must be used. Execution time is proportional to the value input for NRL.

IACD(1)...

IACD(NPROB) indicate, for this fault, which of the attenuation functions is to be used in calculating risks for each of the problems examined in this execution of the program. Typically, if ground acceleration and velocity are to be examined, IACD(1) will indicate an acceleration attenuation function and IACD(2) a velocity attenuation function. Alternately, two or more acceleration attenuation functions may be specified with card 3; then IACD(1) indicates which of these functions apply to this fault.

CARD 9, FORMAT (7F6.3). AMMIN, AMSTEP, RATE, BETA, ECIN, DEPTH, COEF.

AMMIN	is the minimum magnitude to be used in calculations for this fault.
AMSTEP	is the step size used in numerical integration over magnitude. Execution time is inversely proportional to the value input for AMSTEP. A value between 0.1 and 0.5 should be adequate for most problems.
RATE	is the mean number of events per year occurring on this fault, between AMMIN and the maximum magnitude.
BETA	is the parameter of the exponential magnitude distribution; it is ln (10) times the "Richter b" value of the log number versus magnitude relation.
ECIN	is the distance between successive locations of the earthquake rupture zone, as the rupture zone is moved (computationally) along the fault to account for all possible locations. Execution time of the program is inversely proportional to the value input for ECIN. A value between 1 and 10 kilometers should be adequate for most problems.

DEPTH	is the depth of the source. Closest distance to the rupture is calculated using this depth, so if surface rupture is anticipated, a value of zero for depth may be appropriate. On the other hand, if the primary source of seismic energy is thought to be at some depth, a value greater than zero is appropriate even if surface rupture is expected.
COEF	is a weighting coefficient for this fault. Its typical value is unity; however, a value between zero and one may be used to indicate subjective probability on the existence of this fault. (As in the case of probabilities associated with maximum magnitudes discussed above, multiplying expected numbers by the value of COEF results in accurate calculations of risks only when the risks are less than about 0.1. This includes the vast majority of situations for which seismic risk analyses are performed.)

CARD 10, FORMAT (I3,3X,10F6.3). NMAX,AMMAX(1),PMAX(1),...AMMAX(NMAX), PMAX(NMAX).

This card allows a discrete distribution on maximum magnitude to be specified for this fault.

NMAX	is the number of maximum magnitudes used to specify this distribution. NMAX must be between 1 and 5.
AMMAX(1)	is the lowest magnitude which is considered possible for the maximum magnitude on this fault, and
PMAX(1)	is the associated probability.
AMMAX(NMAX)	is the highest magnitude which is considered possible for the maximum magnitude on this fault, and
PMAX(NMAX)	is its probability.

Values for array AMMAX for elements between 1 and NMAX indicate other possible maximum magnitudes, in increasing order, and elements of array PMAX between 1 and NMAX contain the associated probabilities. The sum of probabilities in array PMAX must be unity.

When choosing values for array AMMAX and for variables AMMIN and AMSTEP on card 8, the magnitude step size AMSTEP should be evenly divisible into the magnitude ranges AMMAX(1)-AMMIN,AMMAX(2)-AMMIN,... AMMAX(NMAX)-AMMIN. Otherwise, small errors will be made by the program in calculating risks.

CARD 11, FORMAT (3F6.3). AL,BL,SIGL.

These variables are parameters in the log rupture versus magnitude relation:

$$\text{mean } \log_{10} L_r = AL + BL*M$$

where L_r is rupture length (in units consistent with the distance used in the attenuation functions and with the X-Y locations of fault points), and M is magnitude. SIGL indicates the standard deviation of the uncertainty in this relationship (that is, SIGL is the standard deviation of $\log_{10} (L_r)$. If no uncertainty is desired, specify a small value (0.01) for SIGL, rather than exactly zero, or set NRL=1 on card 8. If SIGL is specified to be less than 0.02, NRL will be set to 1 automatically by the program.

There must be NFP of the following cards:

CARD 12, FORMAT (2F6.3). FX,FY.

FX and FY — are locations of the points which define the straight line segments comprising the fault. Two successive points cannot be coincident.

GUIDELINES FOR PROGRAM USE

Experience with running FRISK to determine seismic risk for a wide variety of problems has lead to several guidelines which users should consider, to avoid unnecessarily long computer runs and inaccurate assessments of seismic hazard. These guidelines apply to typical problems in seismic hazard analysis, and may have to be altered in special cases.

FRISK was designed to be efficient for hazard calculations which model the seismic energy source as a rupture length; as a result, this program is inefficient (but accurate) when used to model point energy sources (that is, sources with rupture lengths of zero). If the source of energy release during an earthquake is modeled as a point rather than as a rupture zone, the user should probably use a program other than FRISK to calculate seismic hazard. Several programs are available (for instance, McGuire, 1976) which make hazard calculations for point sources more efficiently, because (a) numerical integration on magnitude is done inside, rather than outside, numerical integration on location, and (b) if certain typical conditions on the magnitude distribution and attenuation function are met, integration on magnitude can be done analytically for point sources rather than numerically.

Much development work has been done to determine the "best" values for variables NRL, AMSTEP, and ECIN, which control the numerical integrations (see the section on "Required Input"). "Best" in this context means values of the variables which allow accurate calculations with maximum efficiency (lowest computer run time). Suggested values are NRL=4, AMSTEP=0.5, and ECIN=10. A typical seismic hazard problem is shown in figure 6, and the acceleration with 0.01 annual risk at each site was determined using the above suggested values for NRL, AMSTEP, and ECIN. These accelerations are shown in figure 7. Differences in accelerations obtained using other values for NRL, AMSTEP, and ECIN are shown in figure 8. Larger values of ECIN may be used, with little decrease in accuracy; however, it is suggested that the ratio of fault length to ECIN should exceed 20. Similarly, the ratio of the magnitude range to AMSTEP should be five or larger.

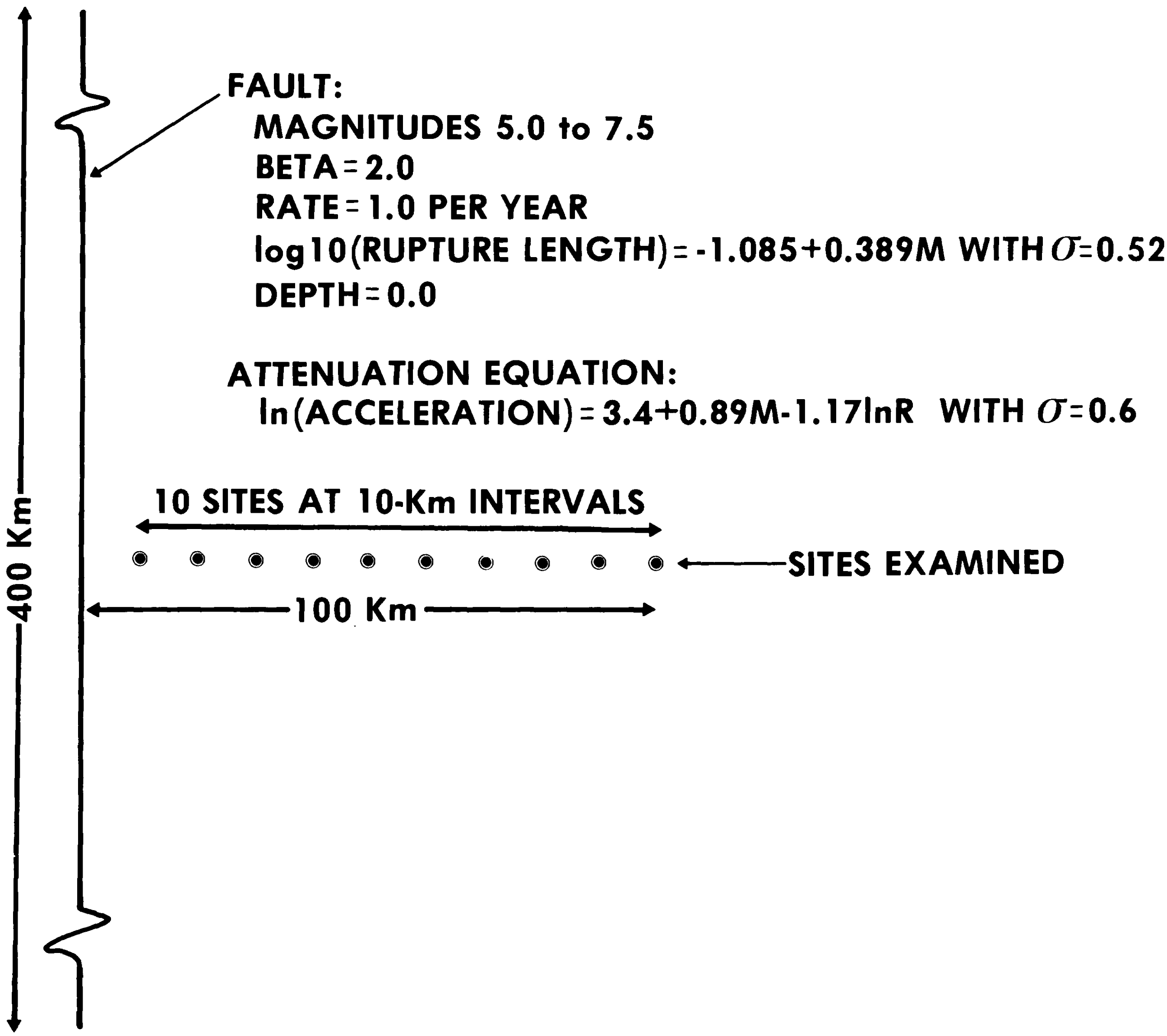


Figure 6.--Geometry and parameters of seismic risk problem used to examine sensitivity of program to NRL-AMSTEP, and ECIN.

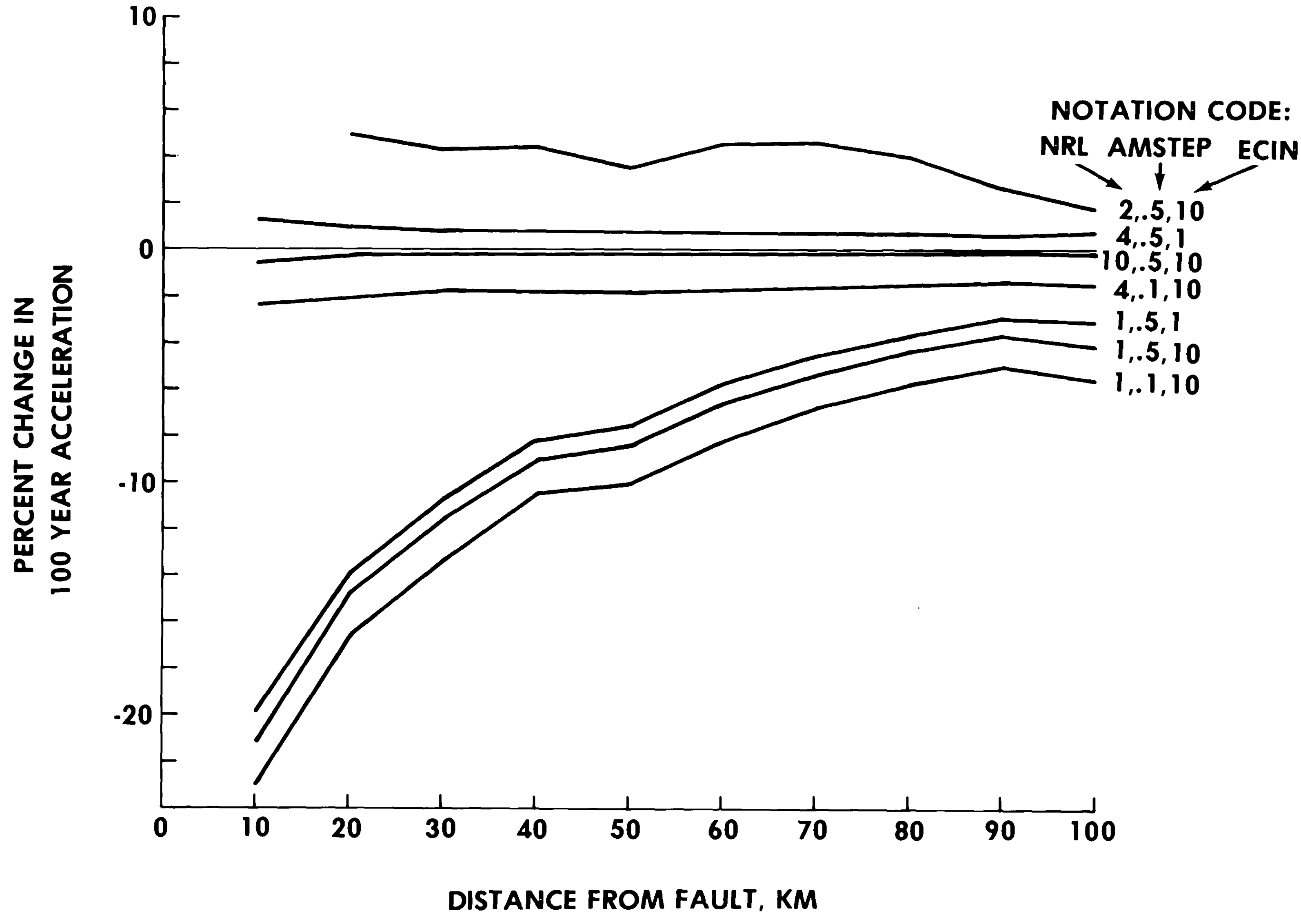


Figure 8.--Changes in 100-year accelerations using alternate values for NRL, AMSTEP, and ECIN.

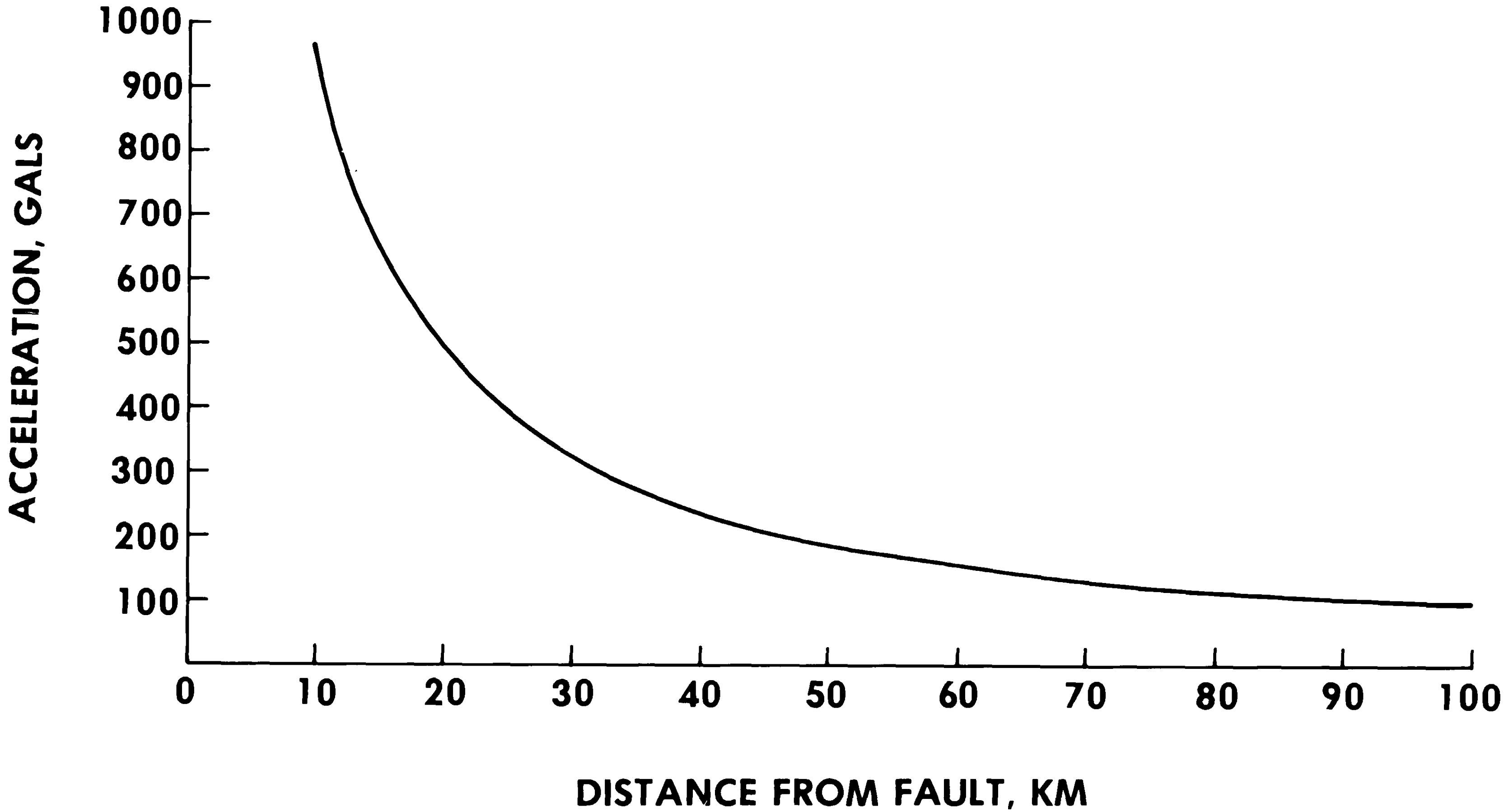


Figure 7.--Acceleration with 0.01 probability of being exceeded at sites 10 to 100 km from fault, using NRL=4, AMSTEP=0.5, and ECIN=10.

On the U.S. Geological Survey's Honeywell Multics[1] computer, execution time of the program can be estimated with the following equation:

Execution Time (C.P.U. seconds)

$$= \left(\frac{\text{Fault length}}{\text{ECIN}}\right)\left(\frac{\text{Mag. Range}}{\text{AMSTEP}}\right)(\text{NRL})(\text{NPROB})^{0.7}(\text{NLEI})^{0.5}(\text{NSITE})^{0.9}\,\frac{1}{500} \qquad (10)$$

Equation 10 assumes that all problems have the same value input for variable NLEI. For more than one fault, the right side of equation 10 should be summed for all faults to estimate execution time. From the form of this equation, it is evident that changes in run time are proportional to changes in values of variables NRL, AMSTEP, and ECIN. Thus these variables should be changed only with extreme caution. Changing each by a factor of 10 could increase execution time by a factor of one thousand! For other computers the constant 1/500 in equation 10 will change, but the influences of the variables will not. Execution time increases less than proportionately to NPROB, NLEI, and NSITE, because integrations over magnitude, location, and length of rupture are done only once for all problems, amplitudes, and sites. Faults specified by a large number of line segments require somewhat more execution time than faults of the same length which are straight.

---

[1]Use of brand names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

A note of caution should be expressed with regard to including uncertainty in the magnitude-rupture-length equation. While such uncertainty may be inherent in available data, including it in seismic hazard analyses can, in certain instances, result in excessive conservatism. If the variable of interest is peak ground acceleration, a longer-than-expected rupture length for a given magnitude earthquake may correspond to a smaller-than-expected average stress drop over the fault. If this low average stress drop could be expected to generate lower-than-average peak accelerations at a site, not accounting for these lower accelerations in the attenuation equation would result in conservative estimates of the risk, at acceleration levels which are generally of interest. Thus it may be more accurate to ignore the uncertainty in rupture length given magnitude, and do the hazard analysis as if the magnitude-rupture length relationship were a deterministic one.

FRISK was written to take advantage of repeated calculations. Thus, to solve seismic hazard problems, it is most efficently used when calculations are made during one execution for multiple sites and for all problems and ground motion amplitudes of interest (peak-ground acceleration, velocity, displacement, spectral velocity, and so on), rather than making repeated executions.

EXAMPLE PROBLEM

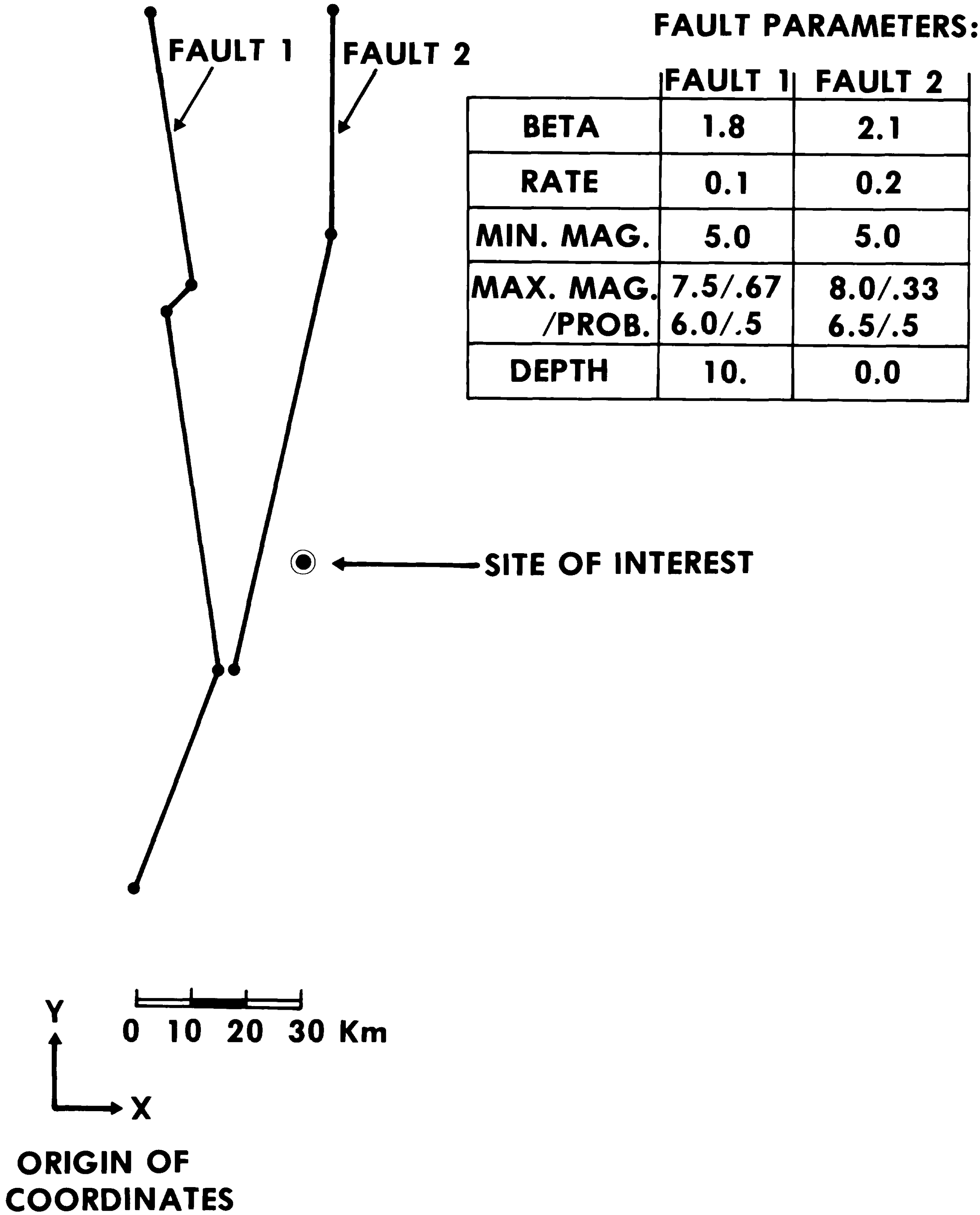
An example problem is described in this section, to illustrate the use of various features of program FRISK. Input and output are listed in Appendix A below.

The geometry of the faults and the site are shown in figure 9, along with the values of parameters used to define seismicity on the faults. For both faults the rupture length-magnitude relation used is

$$\text{mean}_{\log_{10} L_r} = -1.085 + 0.389\ M \tag{11}$$

with a standard deviation of 0.52.

Four attenuation equations are epecified and are used to calculate probabilities for three problems: two for acceleraton and one for velocity. In the first problem (labeled "McGuire 78 Accel") the first attenuation equation (which is for ground acceleration) is used for both faults. In the second problem (labeled "Donovan 73 Accel") the second attenuation equation is used. Thus the only difference between the two problems is the attenuation equation. In the third problem, which calculates risks associated with ground velocities, the third attenuation equation is used for fault 1 and the fourth equation for fault 2, to model different velocities that these faults are thought to produce.



FAULT PARAMETERS:

	FAULT 1	FAULT 2
BETA	1.8	2.1
RATE	0.1	0.2
MIN. MAG.	5.0	5.0
MAX. MAG./PROB.	7.5/.67 6.0/.5	8.0/.33 6.5/.5
DEPTH	10.	0.0

Figure 9.--Faults and site in example problem.

For both faults, step-truncated exponential distributions (figures 3 and 4) are used to describe the distribution of magnitudes, with steps at magnitudes 7.5 and 8 for fault 1 and at 6.0 and 6.5 for fault 2. The minimum magnitude for both faults is magnitude 5.

Output from the program is shown in Appendix A. Risks are calculated for the specified levels of amplitude (acceleration in the first two problems, and velocity in the third). Additionally, amplitude levels are estimated for annual risks of 0.01, 0.002, and 0.001 by interpolation, as described in the section on "Theoretical Background."

Execution time for this problem was 12.5 seconds on a Honeywell Multics computer.

REFERENCES

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________(1971), "Probabilistic Analysis of Damage to Structures under Seismic Loads," Chapter 27 in Dynamic Waves in Civil Engineering, edited by D. A. Howells, I. P. Haigh, and C. Taylor, Wiley Interscience.

Der Kiureghian, Armen, and Ang, A. H-S. (1975), "A Line Source Model for Seismic Risk Analysis," University of Illinois Technological Report, UILU-ENG-75-2023, Ureana, 134 pp, October.

________(1977), "A Fault-Rupture Model for Seismic Risk Analysis," Bulletin Seismological Society of America, v. 67, no. 4, pp 1173-1194, August.

McGuire, R. K. (1974), "Seismic Structural Response Risk Analysis, Incorporating Peak Response Regressions on Earthquake Magnitude and Distance," Massachusetts Institute of Technology, Department of Civil Engineering Report, R74-51, Cambridge, 371 pp, August.

____________(1976). "Fortran Computer Program for Seismic Risk Analysis," U.S. Geological Survey Open-File Report 76-67, 90 pp.

____________(1977). "Effects of Uncertainty in Seismicity on Estimates of Seismic Hazard for the East Coast of the United States," Bulletin Seismological Society of America, v. 67, no. 3, pp 827-848, June.

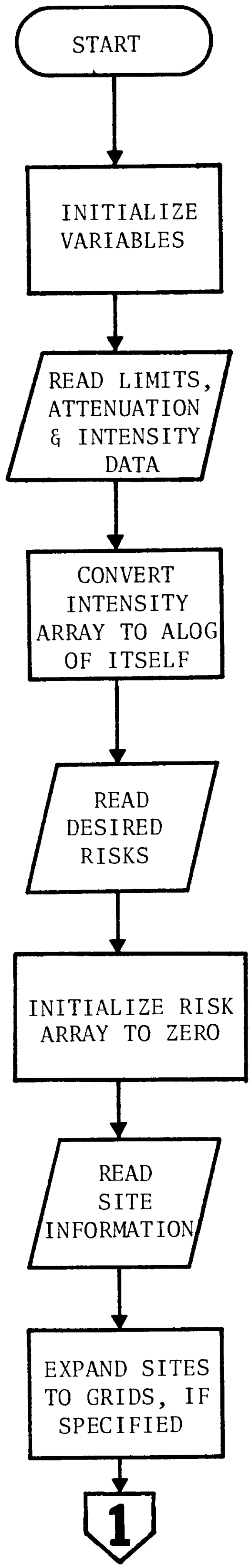
APPENDIX A, EXAMPLE PROBLEM INPUT AND OUTPUT

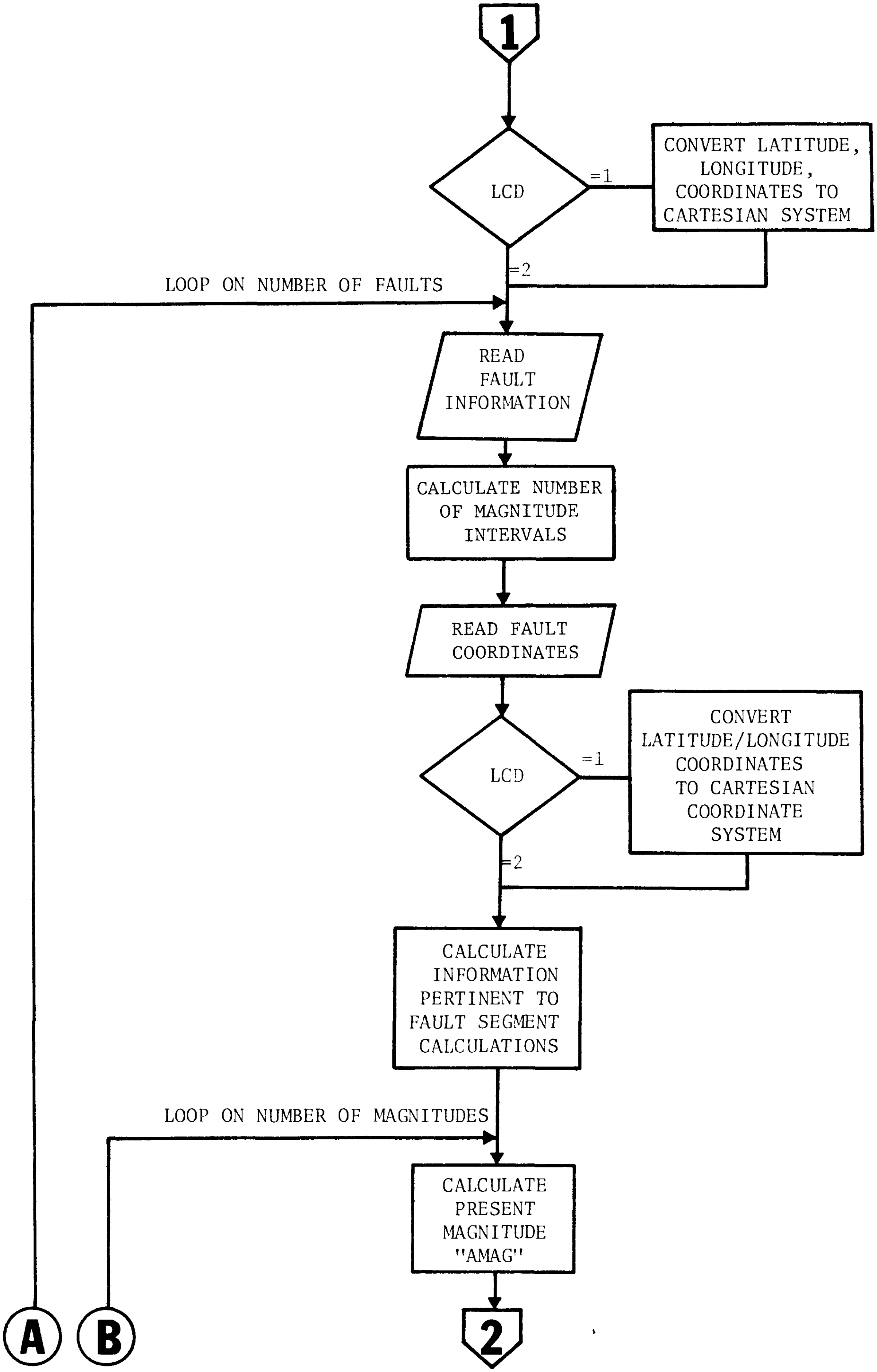
```
example problem for open-file report
  2  1  3  4  2
  5.85  .961 -1.77   25.   .636
  6.98   0.5 -1.32   25.   .707
 -2.55  1.17 -.729    0.   .657
 -1.41  1.21 -1.01   10.   .649
McGuire 78 accel
 10       50.  100.  150.  200.  300.  400.  500.  600.  800. 1000.
Donovan 73 accel
 10       50.  100.  150.  200.  300.  400.  500.  600.  800. 1000.
velocity (comb.)
 10.       5.   10.   15.   20.   25.   30.   40.   50.   60.   80.
  3      0.01 0.002 0.001
   50.   100.
  5  4  1  2  3
    5.     .5    .1   1.8   10.   10.   1.0
  2       7.5   .67   8.0   .33
-1.085 0.389   .52
   15.    40.
   30.    80.
   20.   145.
   25.   150.
   17.   200.
  3  4  1  2  4
   5.0  0.25   0.2   2.1    5.   0.0   1.0
  2       6.0   0.5   6.5   0.5
-1.085 0.389  0.52
   33.    80.
   50.   160.
   50.   200.
```

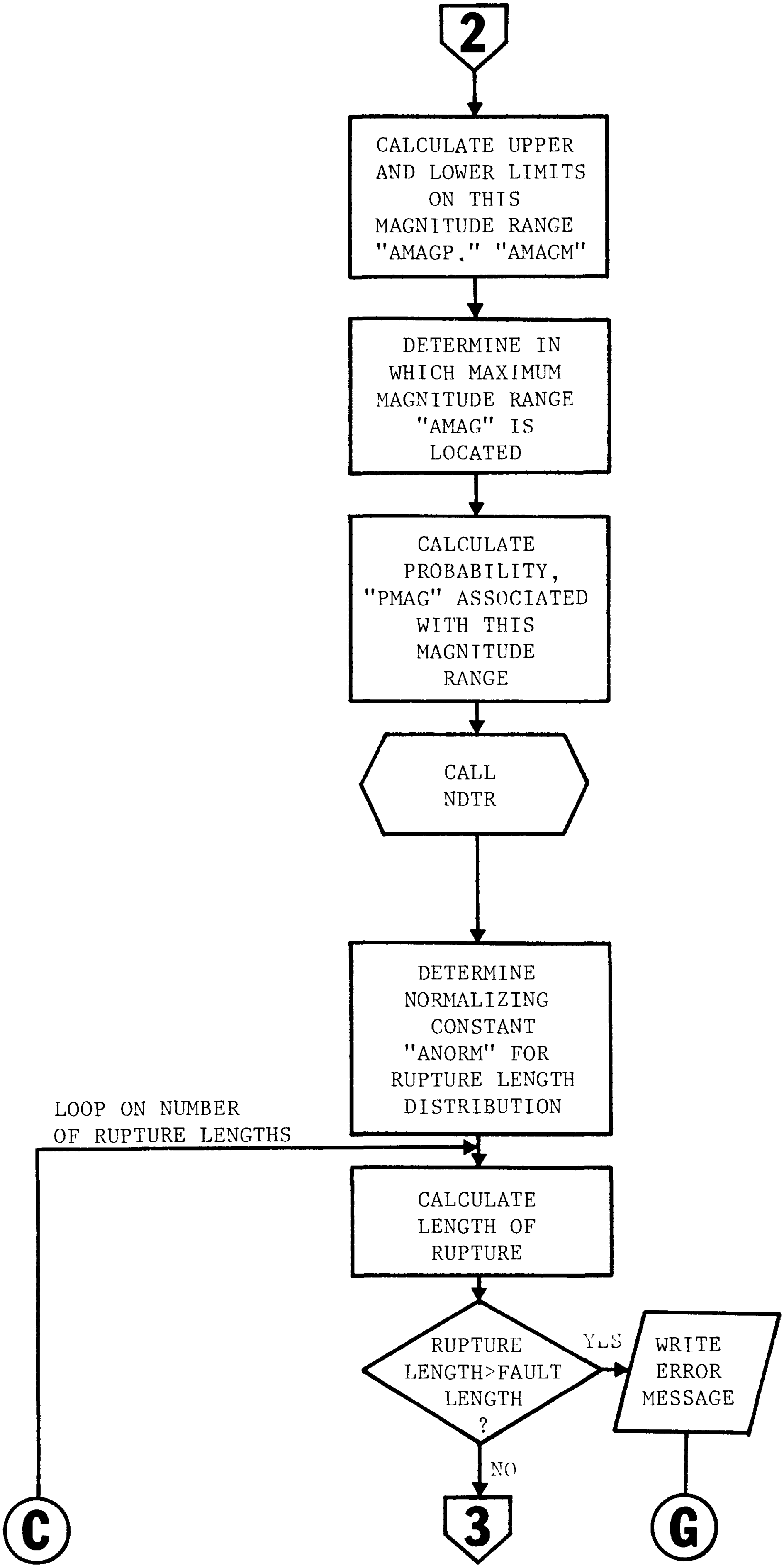
```
title: example problem for open-file report

nflt  nsite   nprob   natt    lcd
 2      1       3       4       2

       c1         c2         c3        rzero       siga
 1     5.850      0.961     -1.770     25.000      0.636
 2     6.980      0.500     -1.320     25.000      0.707
 3    -2.550      1.170     -0.729      0.000      0.657
 4    -1.410      1.210     -1.010     10.000      0.649

problem data:

McGuire 78 accel amplitudes:
    10        50.000  100.000  150.000  200.000  300.000  400.000  500.000  600.000  800.000 1000.000

Donovan 73 accel amplitudes:
    10        50.000  100.000  150.000  200.000  300.000  400.000  500.000  600.000  800.000 1000.000

velocity (comb.) amplitudes:
    10         5.000   10.000   15.000   20.000   25.000   30.000   40.000   50.000   60.000   80.000

risks specified:
  3       0.0100    0.0020    0.0010

site coordinates:
 1       50.000   100.000


fault information:

----------------------------------------------------------------------------

fault 1

nfp    nrl   attenuation codes:
 5      4       1  2  3

ammin   amstep  rate   beta   ecin    deptn   coef
5.000   0.500   0.100  1.800 10.000   10.000  1.000

nmax ammax  pmax
 2    7.50  0.67
      8.00  0.33


   al          bl        sigl
 -1.085      0.389      0.520

fault segment coordinates
 1        15.000     40.000
 2        30.000     80.000
 3        20.000    145.000
 4        25.000    150.000
 5        17.000    200.000

----------------------------------------------------------------------------
```

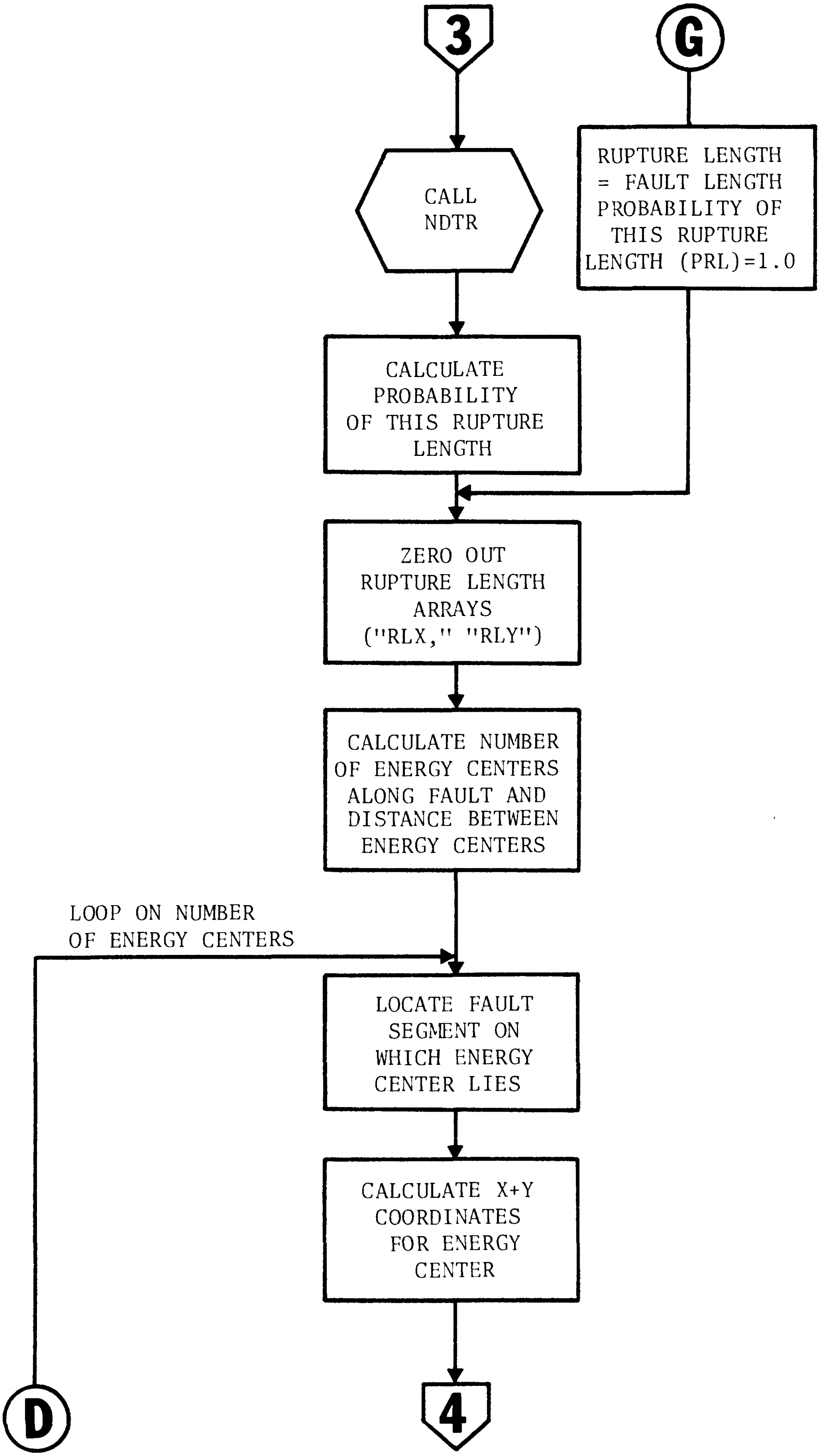
```
fault 2

nfp     nrl    attenuation codes:
 3       4        1  2  4

ammin    amstep   rate   beta    ecin     depth   coef
5.000    0.250   0.200  2.100   5.000     0.000  1.000

nmax ammax   pmax
 2    6.00   0.50
      6.50   0.50


   al          bl        sigl
 -1.085      0.389      0.520

fault segment coordinates
 1        33.000     80.000
 2        50.000    160.000
 3        50.000    200.000


------------------------------------------------------------------------------------------------------------------

site 1 coordinates:     50.000  100.000

McGuire 78 accel amp.:        50.00      100.00      150.00      200.00      300.00      400.00      500.00      600.00      800.00     1000.00
log (amplitude):               3.91        4.61        5.01        5.30        5.70        5.99        6.21        6.40        6.68        6.91
    fault 1 e(no/yr)        0.476e-01 0.230e-01 0.129e-01 0.814e-02 0.393e-02 0.223e-02 0.139e-02 0.927e-03 0.463e-03 0.257e-03
    fault 2 e(no/yr)        0.104e+00 0.601e-01 0.371e-01 0.239e-01 0.110e-01 0.555e-02 0.303e-02 0.176e-02 0.676e-03 0.295e-03
    total   e(no/yr)        0.152e+00 0.830e-01 0.501e-01 0.321e-01 0.149e-01 0.778e-02 0.443e-02 0.269e-02 0.114e-02 0.553e-03
    total risk              0.141e+00 0.797e-01 0.488e-01 0.316e-01 0.148e-01 0.775e-02 0.442e-02 0.268e-02 0.114e-02 0.552e-03

    specified risks:          0.010000  0.002000  0.001000
    estimated log amp. :       5.878     6.496     6.725
    estimated amplitude:      357.127   662.169   832.609

Donovan 73 accel amp.:        50.00      100.00      150.00      200.00      300.00      400.00      500.00      600.00      800.00     1000.00
log (amplitude):               3.91        4.61        5.01        5.30        5.70        5.99        6.21        6.40        6.68        6.91
    fault 1 e(no/yr)        0.667e-01 0.364e-01 0.210e-01 0.128e-01 0.549e-02 0.269e-02 0.145e-02 0.837e-03 0.325e-03 0.146e-03
    fault 2 e(no/yr)        0.138e+00 0.848e-01 0.549e-01 0.368e-01 0.181e-01 0.966e-02 0.551e-02 0.330e-02 0.133e-02 0.606e-03
    total   e(no/yr)        0.205e+00 0.121e+00 0.758e-01 0.497e-01 0.236e-01 0.124e-01 0.696e-02 0.414e-02 0.166e-02 0.751e-03
    total risk              0.185e+00 0.114e+00 0.730e-01 0.484e-01 0.233e-01 0.123e-01 0.693e-02 0.413e-02 0.166e-02 0.751e-03

    specified risks:          0.010000  0.002000  0.001000
    estimated log amp. :       6.072     6.625     6.827
    estimated amplitude:      433.337   754.026   922.428

velocity (comb.) amp.:         5.00       10.00       15.00       20.00       25.00       30.00       40.00       50.00       60.00       80.00
log (amplitude):               1.61        2.30        2.71        3.00        3.22        3.40        3.69        3.91        4.09        4.38
    fault 1 e(no/yr)        0.372e-01 0.162e-01 0.907e-02 0.582e-02 0.405e-02 0.298e-02 0.178e-02 0.116e-02 0.803e-03 0.428e-03
    fault 2 e(no/yr)        0.887e-01 0.438e-01 0.245e-01 0.148e-01 0.946e-02 0.631e-02 0.310e-02 0.168e-02 0.971e-03 0.377e-03
    total   e(no/yr)        0.126e+00 0.600e-01 0.336e-01 0.206e-01 0.135e-01 0.929e-02 0.488e-02 0.284e-02 0.177e-02 0.805e-03
    total risk              0.118e+00 0.582e-01 0.330e-01 0.204e-01 0.134e-01 0.925e-02 0.487e-02 0.283e-02 0.177e-02 0.805e-03

    specified risks:          0.010000  0.002000  0.001000
    estimated log amp. :       3.363     4.047     4.303
    estimated amplitude:      28.872    57.248    73.918
```

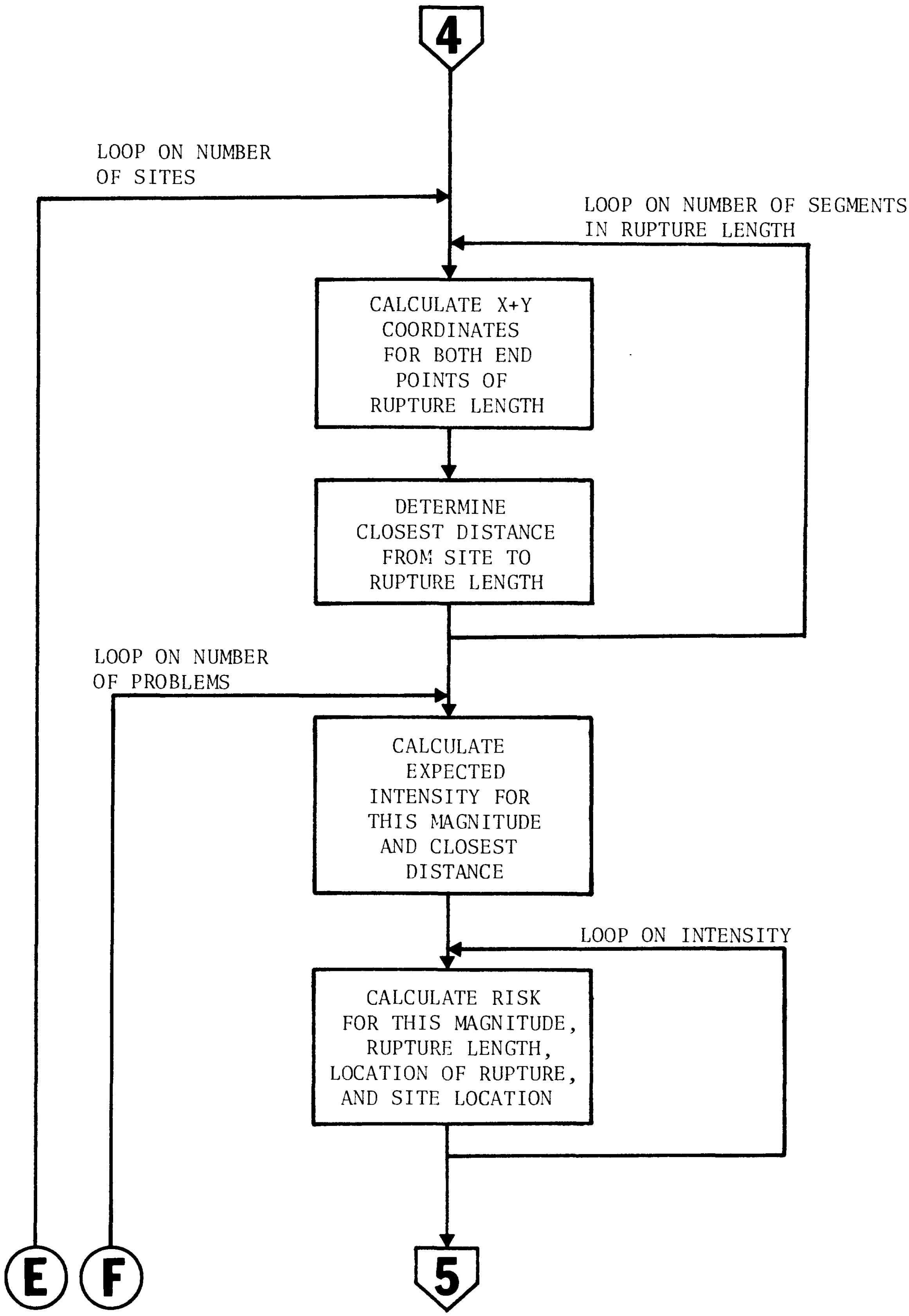
APPENDIX B, PROGRAM FLOW CHART

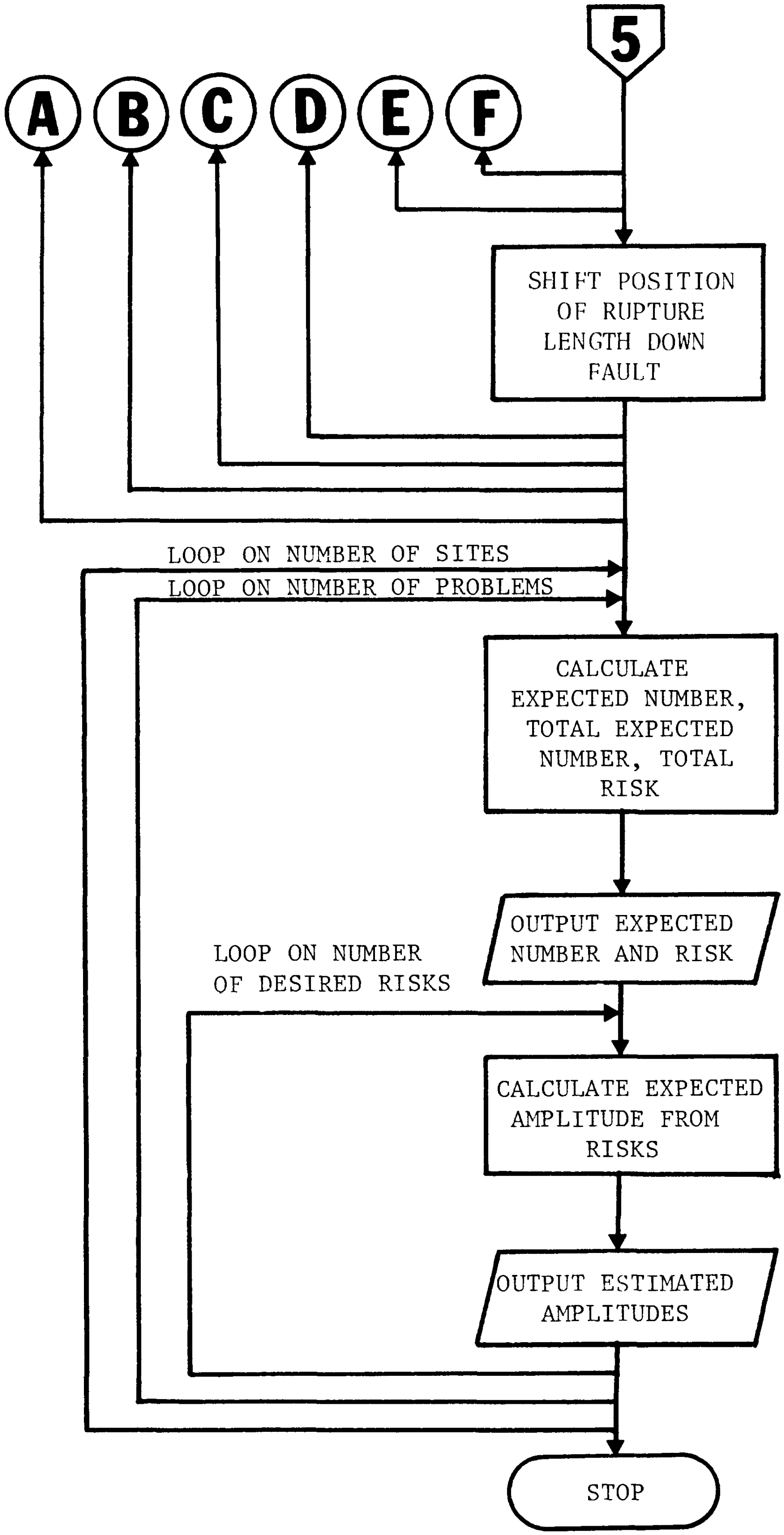

START
INITIALIZE VARIABLES
READ LIMITS, ATTENUATION & INTENSITY DATA
CONVERT INTENSITY ARRAY TO ALOG OF ITSELF
READ DESIRED RISKS
INITIALIZE RISK ARRAY TO ZERO
READ SITE INFORMATION
EXPAND SITES TO GRIDS, IF SPECIFIED
1


1
LCD
=1
CONVERT LATITUDE, LONGITUDE, COORDINATES TO CARTESIAN SYSTEM
=2
LOOP ON NUMBER OF FAULTS
READ FAULT INFORMATION
CALCULATE NUMBER OF MAGNITUDE INTERVALS
READ FAULT COORDINATES
LCD
=1
CONVERT LATITUDE/LONGITUDE COORDINATES TO CARTESIAN COORDINATE SYSTEM
=2
CALCULATE INFORMATION PERTINENT TO FAULT SEGMENT CALCULATIONS
LOOP ON NUMBER OF MAGNITUDES
CALCULATE PRESENT MAGNITUDE "AMAG"
A
B
2


2
CALCULATE UPPER AND LOWER LIMITS ON THIS MAGNITUDE RANGE "AMAGP," "AMAGM"
DETERMINE IN WHICH MAXIMUM MAGNITUDE RANGE "AMAG" IS LOCATED
CALCULATE PROBABILITY, "PMAG" ASSOCIATED WITH THIS MAGNITUDE RANGE
CALL NDTR
DETERMINE NORMALIZING CONSTANT "ANORM" FOR RUPTURE LENGTH DISTRIBUTION
LOOP ON NUMBER OF RUPTURE LENGTHS
CALCULATE LENGTH OF RUPTURE
RUPTURE LENGTH>FAULT LENGTH ?
YES
WRITE ERROR MESSAGE
NO
C
3
G


3
G
CALL NDTR
RUPTURE LENGTH = FAULT LENGTH PROBABILITY OF THIS RUPTURE LENGTH (PRL)=1.0
CALCULATE PROBABILITY OF THIS RUPTURE LENGTH
ZERO OUT RUPTURE LENGTH ARRAYS ("RLX," "RLY")
CALCULATE NUMBER OF ENERGY CENTERS ALONG FAULT AND DISTANCE BETWEEN ENERGY CENTERS
LOOP ON NUMBER OF ENERGY CENTERS
LOCATE FAULT SEGMENT ON WHICH ENERGY CENTER LIES
CALCULATE X+Y COORDINATES FOR ENERGY CENTER
D
4


4
LOOP ON NUMBER
OF SITES
LOOP ON NUMBER OF SEGMENTS
IN RUPTURE LENGTH
CALCULATE X+Y
COORDINATES
FOR BOTH END
POINTS OF
RUPTURE LENGTH
DETERMINE
CLOSEST DISTANCE
FROM SITE TO
RUPTURE LENGTH
LOOP ON NUMBER
OF PROBLEMS
CALCULATE
EXPECTED
INTENSITY FOR
THIS MAGNITUDE
AND CLOSEST
DISTANCE
LOOP ON INTENSITY
CALCULATE RISK
FOR THIS MAGNITUDE,
RUPTURE LENGTH,
LOCATION OF RUPTURE,
AND SITE LOCATION
E
F
5


5
A
B
C
D
E
F
SHIFT POSITION OF RUPTURE LENGTH DOWN FAULT
LOOP ON NUMBER OF SITES
LOOP ON NUMBER OF PROBLEMS
CALCULATE EXPECTED NUMBER, TOTAL EXPECTED NUMBER, TOTAL RISK
OUTPUT EXPECTED NUMBER AND RISK
LOOP ON NUMBER OF DESIRED RISKS
CALCULATE EXPECTED AMPLITUDE FROM RISKS
OUTPUT ESTIMATED AMPLITUDES
STOP

APPENDIX C. PROGRAM LISTING

```
c   program "frisk" for fault risk analysis
c   designed by r.k. mc guire
c   coded by v.l. opfer
c   u.s.g.s.  december, 1977 golden colorado
        dimension sitex(2,50),sitey(2,50),fx(2,20),fy(2,20)
        dimension xf(2),risk(10,5,50,12),ti(5,10),tif(10),riskd(10)
        dimension fsl(20),fsa(20),fsb(20),ind(20),ati(5,10)
        dimension cuml(20),alp(20),clp(20),rlx(20),rly(20),x3(2),y3(2)
        dimension desc(6,4),c1(5),c2(5),c3(5),siga(5),iacd(5),nlei(5)
        dimension rzero(5),title(20),ammax(5),omax(5)
c   **the above array sizes were chosen to minimize excess storage. if
c   larger arrays are needed, the subscripts are organized as follows:
c   risk(nlei,nprob,nsite,nflt)    ati(nprob,nlei)
c   sitex(lcd,nsite)  sitey(lcd,nsite)  fx(lcd,nfp)  fy(lcd,nfp)
c   ti(nprob,nlei)    desc(nprob,1-4)     *******************************
c   ***********************************************************
c   if you have problems fitting this program on your computer,
c   change dimension in array "risk" to suit your needs (e.g. if
c   you are analyzing only 1 site, change the 3rd dimension from
c   50 to 1)
c   ***********************************************************
c   the limitations on fsl,fsa,fsb, and other arrays dimensioned
c   to 20 are the number of fault segment coordinates used to
c   describe the fault.
c   "rd" is input device number  "wr" is output device number
c   "data" is output number for data echo output
        nrd=2
        nwr=3
        ndata=3
        isite=0
        c=0.01745329252
        r=6371.0
        cr=c*r
        cuml(1)=0
        read(nrd,10)(title(i),i=1,20)
c   title is the actual title given to the output file
  10    format(20a4)
        write(ndata,12)(title(i),i=1,20)
  12    format(//1x,"title: ",20a4)
        if(wr.eq.data)go to 15
        write(nwr,12)(title(i),i=1,20)
  15    read(nrd,20)nflt,nsite,nprob,natt,lcd
c   nflt=number of faults to be studied.  nsite=number of sites
c   nprob=number of problems  natt=number of attenuation functions
c   lcd=1 means data is in lat, long form. lcd=2 indicates x y input.
  20    format(20i3)
        write(ndata,30)nflt,nsite,nprob,natt,lcd
  30    format(/" nflt  nsite   nprob   natt     lcd",/i3,5x,i2,3(6x,i2))
        write(ndata,40)
        do 50 i=1,natt
        read(nrd,35)c1(i),c2(i),c3(i),rzero(i),siga(i)
  35    format(10f6.3)
  40    format(/8x,"c1",8x,"c2",8x,"c3",5x,"  rzero      siga")
  50    write(ndata,60)i,c1(i),c2(i),c3(i),rzero(i),siga(i)
  60    format(1x,i2,5f10.3,2x)
        write(ndata,70)
  70    format(/" problem data:")
        do 100 i=1,nprob
        read(nrd,10)(desc(i,j1),j1=1,4)
        write(ndata,80)(desc(i,j1),j1=1,4)
```

```
80      format(/1x,4a4," amplitudes:")
c  desc is the description of the attenuation function
c  example: velocity, or acceleration
        read(nrd,85)nlei(i),(ati(i,j),j=1,nlei(i))
c  nlei is number of intensities to be studied, ati contains
c  the intensities.
85      format(i3,3x,10f6.3)
        write(ndata,90)nlei(i),(ati(i,j),j=1,nlei(i))
90      format(3x,i4,4x,10f9.3)
        do 100 j1=1,nlei(i)
100     ti(i,j1)=alog(ati(i,j1))
c  read in desired risks:
        read(nrd,85)nrskd,(riskd(ik),ik=1,nrskd)
        write(ndata,105)nrskd,(riskd(ik),ik=1,nrskd)
105     format(/" risks specified:"/,1x,i3,3x,8f10.4)
        do 110 i1=1,nsite
        do 110 i2=1,nprob
        do 110 i3=1,nflt+1
        do 110 i4=1,nlei(i2)
110     risk(i4,i3,i2,i1)=0.0
c  read in site file
        write(ndata,120)
120     format(/" site coordinates:")
        do 175 i=1,nsite
        read(nrd,160)sx,sy,nx,ny,dx,dy
        if(nx.eq.0)nx=1
        if(ny.eq.0)ny=1
        do 140 j=1,ny
        do 140 k=1,nx
        isite=isite+1
        sitey(lcd,isite)=sy+dy*(j-1)
        sitex(lcd,isite)=sx+dx*(k-1)
140     write(ndata,150)isite,sitex(lcd,isite),sitey(lcd,isite)
150     format(1x,i2,3x,2f10.3)
160     format(2f6.2,2i3,2f6.2)
175     continue
        if(lcd.ne.1)go to 200
c  calculate site coordinates in cartesian form
        do 180 i2=1,isite
        avx=avx+sitex(1,i2)
180     avy=avy+sitey(1,i2)
        t=isite
        avx=avx/t
        avy=avy/t
        zz=cos(avy*c)*cr
        do 190 i2=1,isite
        sitex(2,i2)=(sitex(1,i2)-avx)*zz
190     sitey(2,i2)=(sitey(1,i2)-avy)*cr
200     write(ndata,210)
210     format(//" fault information:")
c  "do 900" is the loop in faults
        do 900 jf=1,nflt
        write(ndata,220)jf
220     format(/1x,77("-")//" fault",i2)
        read(nrd,20)nfp,nrl,(iacd(i),i=1,nprob)
        write(ndata,240)nfp,nrl,(iacd(i),i=1,nprob)
240     format(/" nfp    nrl   attenuation codes:",/1x,i2,i7,4x,10i3)
        do 250 kk=1,nprob
        if(iacd(kk).gt.natt)write(ndata,260)iacd(kk)
250     if(iacd(kk).gt.natt)iacd(kk)=0
```

```
 260    format(//" ***invalid attenuation code",i2,
     1 "  will default to zero and continue***"//)
        read(nrd,35)ammin,amstep,rate,beta,ecin,depth,coef
        write(ndata,270)ammin,amstep,rate,beta,ecin,depth,coef
 270    format(/" ammin   amstep   rate   beta   ecin   depth",
     1 "    coef",/1x,f5.3,2f8.3,2f7.3,f8.3,f7.3)
        read(nrd,85)nmax,(ammax(i),pmax(i),i=1,nmax)
        write(ndata,290)nmax,(ammax(i),pmax(i),i=1,nmax)
 290    format(/" nmax ammax  pmax"/,1x,i2,2x,2(1x,f5.2)/,9(5x,2(1x,f5.2),
     1 /))
        read(nrd,35)al,bl,sigl
        write(ndata,300)al,bl,sigl
 300    format(/"    al",9x,"bl      sigl",/1x,f7.3,2f10.3)
        if(sigl.le.0.02)nrl=1
        if(sigl.le.0.02)write(ndata,280)
 280    format(/" small uncertainty in rupture length, nrl set = 1")
        nmag=(ammax(nmax)-ammin+0.01)/amstep
c   srl indicates limits on integration over uncertainy in log10
c   (rupture length), in standard deviations.
        srl=2.0
        anrl=nrl
        delrl=2.*srl/anrl
c   read in fault segment coordinates
        write(ndata,310)
 310    format(/" fault segment coordinates")
        do 320 i=1,nfp
        read(nrd,35)fx(lcd,i),fy(lcd,i)
        write(ndata,150)i,fx(lcd,i),fy(lcd,i)
        if(lcd.ne.1)go to 320
c   calculate fault point coordinates in cartesian form
        fx(2,i)=(avx-fx(1,i))*zz
        fy(2,i)=(avy-fy(1,i))*cr
 320    continue
 350    do 360 i=2,nfp
        xdelta=fx(2,i)-fx(2,i-1)
        ydelta=fy(2,i)-fy(2,i-1)
c   calculate distance between points, slope of line equation
        fsl(i)=(xdelta*xdelta+ydelta*ydelta)**.5
        if(abs(xdelta).lt.0.0001)go to 355
c   fsa is the slope of the segment line equation
c   fsb is the x y intercept of the segment line equation.
        fsa(i)=ydelta/xdelta
        fsb(i)=fy(2,i-1)-fsa(i)*fx(2,i-1)
 355    ind(i)=1
        if(abs(xdelta).lt.0.0001)ind(i)=2
        if(abs(ydelta).lt.0.0001)ind(i)=0
c   ind=0 indicates 0 slope.
c   ind=1 indicates normal slope
c   ind=2 indicates infinite slope
        cuml(i)=cuml(i-1)+fsl(i)
 360    continue
c   calculate segment distance as percentage of entire fault length,
c   and cum distance percent
        do 370 i=2,nfp
        alp(i)=fsl(i)/cuml(nfp)*100.0
 370    clp(i)=cuml(i)/cuml(nfp)*100.0
c   "do 800" is numerical integration over magnitude
        do 800 im=1,nmag
        a=im
        amag=ammin+a*amstep-amstep/2.
```

```
          amp=amag+amstep/2.
          amm=amag-amstep/2.
          do 380 i=1,nmax
          mrang=i
c  mrang indicates magnitude range with respect to max. magnitudes.
380       if(amag.le.ammax(i))go to 390
390       ak=0.0
          do 400 i=mrang,nmax
400       ak=ak+pmax(i)/(1.-exp(-beta*(ammax(i)-ammin)))
c   pmag is probability of magnitude between amp and amm.
c   Insert an alternative function if the step-truncated
c   exponential is not desired.
          pmag=ak*(exp(-beta*(amm-ammin))-exp(-beta*(amp-ammin)))
          all=alog10(cuml(nfp))
          aa=(all-al-bl*amag)/sigl
          call ndtr(aa,f0,d)
          if(f0.eq.1.0)anorm=0.0
          if(f0.eq.1.0)go to 410
          anorm=1./(1.-f0)
c  "do 700" is numerical integration over length of rupture
410       do 700 irl=1,nrl
          arl=-srl+irl*delrl-delrl/2.
          arlp=arl+delrl/2.
          arlm=arl-delrl/2.
          rl=10.0**(al+bl*amag+arl*sigl)
          if(rl.le.cuml(nfp))go to 430
          if(irl.gt.1)go to 800
          prl=1.0
          write(nwr,420)rl,jf,cuml(nfp),amag
420       format(" **caution** mean-2 sigma rupture length (",f7.3,") is",
     1 " greater than fault",i2," length (",f7.3,").  for magnitude:"
     1 ,f5.3)
          rl=cuml(nfp)
          go to 440
430       call ndtr(arlm,f1,d)
          call ndtr(arlp,f2,d)
          if(irl.eq.1)f1=1.0
          if(irl.eq.nrl)f2=f0
c   prl is probability of rupture length between
c   10.**(al+bl*amag+arlm) and
c   10.**(al+bl*amag+arlp).
c   Insert an alternative function if the lognormal is not desired.
          prl=(f1-f2)*anorm
c  zero out rupture length arrays:
440       do 450 kj=1,20
          rlx(kj)=0
450       rly(kj)=0
c  calculate number of energy centers along fault and the distance
c  between energy centers
          in=(cuml(nfp)-rl)/ecin+1.999
          if(in.eq.1)in=2
c  stsz is energy center step size in percent
          stsz=(100.0-((rl)/cuml(nfp))*100.0)/(in-1)
c  xf(1) is the location in percentage along the fault where the
c  rupture length begins, and xf(2) is the end point, also in %
          xf(1)=0.0
          xf(2)=(rl/cuml(nfp))*100.0
          kseq=1
c  kseg is fault segment on which energy center is located.
c  "do 600" is numerical integration over rupture location
```

```
      do 600 ik=1,in
c  ecp is the energy center location as a percent along the fault length
      ecp=(xf(2)-xf(1))/2.+xf(1)
c  locate segment on which energy center is located
      do 460 kt=kseg,nfp-1
      kseg1=kt+1
460   if(ecp.le.clp(kseg1))go to 470
470   kseg=kt
      b=clp(kseg1)-ecp
      a=alp(kseg1)-b
c  calculate energy center x and y coordinates
      ecx=(b*fx(2,kseg)+a*fx(2,kseg1))/(a+b)
      ecy=(b*fy(2,kseg)+a*fy(2,kseg1))/(a+b)
      do 475 m=1,2
      do 475 n=1,nfp-1
      if(xf(m).gt.clp(n+1))go to 475
      b=clp(n+1)-xf(m)
      a=alp(n+1)-b
c  ns1 is segment on which beginning of rupture length lies
c  ns2 is segment on which end of rupture length lies.
      if(m.eq.1)ns1=n
      if(m.eq.2)ns2=n
c  calculate x and y coordinates for both end points of rupture length
      x3(m)=(b*fx(2,n)+a*fx(2,n+1))/(a+b)
      y3(m)=(b*fy(2,n)+a*fy(2,n+1))/(a+b)
475   continue
c  nsrl is number of segments in rupture length
      nsrl=ns2-ns1+1
      rlx(1)=x3(1)
      rlx(nsrl+1)=x3(2)
      rly(1)=y3(1)
      rly(nsrl+1)=y3(2)
      if (nsrl.eq.1)go to 490
      ji=0
      do 480 j=2,nsrl-1
      ji=ji+1
      rlx(j)=fx(2,ns1+ji)
480   rly(j)=fy(2,ns1+ji)
c***************************************************************
c  coding between asteriks calculates closest distance to this
c  rupture for site jk
c  there are nsrl line segments in this rupture length. points
c  defining rupture are contained in arrays rlx(i) and rly(i) from
c  elements 1 to nsrl + 1.
c  probability of this magnitude is pmag
c  probability of this rupture length is prl
c  probability of this location of rupture length is 1/in
c  site coordinates (x,y) are in arrays sitex(2,jk) and sitey(2,jk)
c  sitex(1,jk) and sitey(1,jk)contain latitude,longitude coordinates,
c  if used.
c  energy center is located at ecx,ecy
490   do 570 jk=1,isite
      cd=99999.
      do 550 k=1,nsrl
      k1=k+1
c  calculate distance from site to both end points of rupture
c  length segment and distance from site to perpendicular dropped
c  on segment length
      s1=((rlx(k)-sitex(2,jk))**2+(rly(k)-sitey(2,jk))**2)**.5
      s2=((rlx(k1)-sitex(2,jk))**2+(rly(k1)-sitey(2,jk))**2)**.5
```

```
         a=fsa(k1)
         if(ind(k1).eq.2)go to 500
         if(ind(k1).ne.0)go to 510
         xp=sitex(2,jk)
         yp=rly(k)
         go to 520
c  xp and yp are the x & y intercepts of the perpendicular from the
c  site to the rupture length.
500      yp=sitey(2,jk)
         xp=rlx(k)
         go to 520
510      xp=(sitey(2,jk)+(sitex(2,jk)/a)-fsb(k1))/(a+(1/a))
         yp=((sitex(2,jk)-xp)/a)+sitey(2,jk)
520      perpl=(((sitex(2,jk)-xp)**2+(sitey(2,jk)-yp)**2))**.5
c  determine closest distance and store it
c  cd is the closest distance from the site to the rupture length.
         cd=amin1(s1,s2,cd)
         if(ind(k1).eq.2)go to 530
         if(xp.ge.rlx(k).and.xp.le.rlx(k1))cd=amin1(perpl,cd)
         if(xp.ge.rlx(k1).and.xp.le.rlx(k))cd=amin1(perpl,cd)
         go to 550
530      if(yp.ge.rly(k).and.yp.le.rly(k1))cd=amin1(perpl,cd)
         if(yp.ge.rly(k1).and.yp.le.rly(k))cd=amin1(perpl,cd)
550      continue
c*****************************************************************
c  "eti" is expected intensity for this magnitude and closest distance
         do 560 jj=1,nprob
         if(iacd(jj).eq.0)go to 560
         eti=c1(iacd(jj))+c2(iacd(jj))*amag+c3(iacd(jj))*alog((cd*cd
      1  +depth*depth)**.5+rzero(iacd(jj)))
         do 560 i=1,nlei(jj)
         w=(ti(jj,i)-eti)/siga(iacd(jj))
         call ndtr(w,g,d)
         ain=in
         risk(i,jj,jf,jk)=risk(i,jj,jf,jk)+coef*rate*g*pmag*prl/ain
560      continue
570      continue
         xf(1)=xf(1)+stsz
         xf(2)=xf(2)+stsz
600      continue
700      continue
800      continue
900      continue
         do 1000 i=1,isite
         write(nwr,910)i,sitex(lcd,i),sitey(lcd,i)
910      format(//,115("-"),//" site",i2," coordinates: ",2f9.3)
         do 1000 j=1,nprob
919      format(" log (amplitude):",7x,10f10.2)
         write(nwr,920)(desc(j,j1),j1=1,4),(ati(j,j2),j2=1,nlei(j))
         write(nwr,919)(ti(j,j2),j2=1,nlei(j))
920      format(/,1x,4a4,1x,"amp.:",1x,10f10.2)
         do 940 k=1,nflt
         do 930 l=1,nlei(j)
930      risk(l,j,nflt+1,i)=risk(l,j,nflt+1,i)+risk(l,j,k,i)
940      write(nwr,950)k,(risk(m,j,k,i),m=1,nlei(j))
950      format("      fault",i2," e(no/yr)",5x,10e10.3)
         write(nwr,960)(risk(m,j,nflt+1,i),m=1,nlei(j))
960      format("      total    e(no/yr)",5x,10e10.3)
         do 970 m1=1,nlei(j)
         if(risk(m1,j,nflt+1,i).lt.0.0001)risk(m1,j,nflt+2,i)=
```

```
     1 risk(m1,j,nflt+1,i)
       if(risk(m1,j,nflt+1,i).lt.0.0001)go to 970
       risk(m1,j,nflt+2,i)=(1-exp(-risk(m1,j,nflt+1,i)))
970    continue
       write(nwr,975)(risk(m,j,nflt+2,i),m=1,nlei(j))
975    format("     total risk",11x,10e10.3)
       if (riskd(1).eq.0.0)go to 1000
       do 985 kk=1,nrskd
       do 980 ll=1,nlei(j)-1
       if(risk(ll+1,j,nflt+2,i).eq.0.0)go to 981
980    if(riskd(kk).lt.risk(ll,j,nflt+2,i).and.riskd(kk).
     1 gt.risk(ll+1,j,nflt+2,i))go to 982
981    tif(kk)=1000000.0
       go to 985
982    tif(kk)=(alog(risk(ll,j,nflt+2,i)/riskd(kk)))/
     1 (alog(risk(ll,j,nflt+2,i)/risk(ll+1,j,nflt+2,i)))
       tif(kk)=ti(j,ll)+tif(kk)*(ti(j,ll+1)-ti(j,ll))
985    continue
       write(nwr,986)(riskd(ik),ik=1,nrskd)
       write(nwr,987)(tif(ij),ij=1,nrskd)
986    format(/"     specified risks:",6x,10f10.6)
987    format("     estimated log amp. :",1x,10(1x,f9.3))
       do 999 il=1,nrskd
       if(tif(il).eq.1000000.0)go to 999
       tif(il)=exp(tif(il))
999    continue
       write(nwr,998)(tif(im),im=1,nrskd)
998    format("     estimated amplitude:",1x,10(1x,f9.3)/)
1000   continue
       stop
       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
```

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Please include my name on the mailing list for corrections/ improvements to computer program FRISK.

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