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CRITERIA FOR SEISMIC GROUND MOTION FOR ESSENTIAL STRUCTURES

by

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The Navy has numerous bases located in seismically active regions throughout the world. Safe and effective structural design of waterfront facilities requires calculating the expected site specific ground motion and determining the response of these complex structures to the induced loading. The Navy's problem is further complicated by the presence of soft saturated marginal soils which can significantly amplify the levels of seismic shaking and liquefy as evidenced by recent earthquake damage. NAVFAC P355.1 requires detemination of a probabilistic ground motion for the design of essential strucutres; however, procedures were not specified to accomplish this requirement. This document presents criteria for computing the expected ground motion for various probabilities of nonexceedance.

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Executive Summary

The Navy has numerous bases located in seismically active regions throughout the world. Safe and effective structural design of waterfront facilities requires calculating the expected site specific ground motion and determining the response of these complex structures to the induced loading. The Navy's problem is further complicated by the presence of soft saturated marginal soils which can significantly amplify the levels of seismic shaking and liquefy as evidenced by recent earthquake damage. NAVFAC P355.1 requires determination of a probabilistic ground motion for the design of essential structures; however, procedures were not specified to accomplish this requirement. This document presents criteria for computing the expected ground motion for various probabilities of nonexceedance.

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CRITERIA

NAVFAC instructions require a probabilistic site seismicity study for essential construction. However, no procedure was specified to accomplish this. This criteria describes acceptable procedures and software.

The objective of a seismicity study is to quantify the level and characteristics of ground motion shaking that pose a risk to a site of interest. The approach taken in this work is to use the historical epicenter data base in conjunction with available geologic data to form a best estimate of the probability distribution of site ground motion.

OUTLINE OF PROCEDURE

Acceptable procedures for conducting a site seismicity must include the following elements. The process consists of building a model of the region to capture the seismic activity. Probabilistic procedures are required per NAVFAC P355.1. The procedure consists of:

- Evaluating the tectonics and geologic settings
- Determining and defining seismic sources
- Determining the geologic seismic slip rate data for sources
- Defining the epicenter search area
- Search of epicenter data base
- Developing an epicenter data base for region of interest
- Specifying and formulating the site seismicity/faulting model
- Developing the regional and fault recurrence models
- Determining the maximum source events
- Selecting the motion attenuation relationship
- Computing individual fault/source seismic contributions
- Summing the sources
- Developing probability distribution for firm site
- Determining local site soil conditions
- Determining the local site response
- Determining the site matched time histories or spectra for causative events

The supporting technical material will present a summary and discussion of the technology for each of the elements of the analysis. A separate guidance document is also available (Ferritto, 1993).

A PROCEDURE FOR COMPUTING SITE SEISMICITY

The objective of the seismicity study is to determine the levels and probability of occurrence of ground motion at the site. As a criteria guide, the following describes a minimum requirement.

Site Study Bounds Site coordinates and the study bounds are to be specified in terms of latitude and longitude. Generally the study zone must extend to the limit distance at which a significant earthquake could cause damage at the site. In the West this extends to about 75 miles but may be over 100 miles in the East.

Development Of Seismicity Model In the Western United States, the tectonic environment is such that earthquakes are associated on known faults. However, in the Eastern United States, the causative geologic structures are generally as well defined. A seismic model must be based on the knowledge of the local area. It can consist of an area source zone for eastern sites or a detailed fault definition region for western sites. Where faults are identified as sources, the area contained within the source zone is defined to have a relatively uniform seismic potential in terms of maximum magnitude and event recurrence. A fault is modeled as a line source encompassing a distance or region surrounding the fault, such that the activity of this region can be associated with events on the fault. Where a fault exhibits variations of activity along its length, it can be divided into subelements containing regions where activity is uniform. A fault segment can be modeled by two line segments defined by three points. The seismic events to include or associate with the fault are defined by specification of the distance from the fault line, such that all those events within that distance are associated with that fault. Alternatively, a region can be designated by four points to bound the fault segment. Again, note a fault can be divided into pieces where activity or geometry so dictates.

In the Eastern United States, faulting may not be readily identifiable. Source zones are specified as regions where a zone of like seismicity is evident. The regional geology and tectonics assist in defining the source zone boundaries. A source zone is defined as a region of uniform seismicity, such that an event is equally likely to occur in any portion of the zone. This is characterized by the concept of a "floating earthquake," an event that can occur anywhere in the zone.

In the development of a site model, it is important to keep in mind that an equivalent representation of a region is being created by a series of fault line segments or source zones. The seismicity must be captured in terms of its spatial location and in terms of the level of activity. Assignment of events to one fault source as opposed to another increases that fault's contribution to the estimation of event recurrence. It is important to capture all the seismicity. For faulting conditions where there are a number of parallel elements, it may not be easy to separate which events are associated with which fault. Consideration must be given to the dip of the fault in assigning events, since the epicenter for a sloping fault can actually occur in a number of kilometers away from the surface trace of the fault. The large majority of strike slip faults have steep dips of 70 degrees or greater. On the other hand, thrust faults generally have dips much less than this, generally in the range of 45 to 60 degrees. Recognition of previous research in establishing recurrence parameters shall be used where available. Such bodies of knowledge are available for California from the CDMG Internet site.

For the cases where a fault is close to a site (within 10 miles), special considerations shall be given to the location of the fault line segments that define the fault model. If the fault dips toward the site, the actual epicentral distance may be closer to the site than the surface trace of the fault. For faults at greater distances, the difference becomes less significant. Three dimensional representation is required for accurate assessment.

Maximum Magnitude Determination Once a fault or region has been defined as a seismic source, the maximum event limiting earthquake magnitude must be defined. The length of a fault can be estimated from maps. An assumption can be made that a fault will rupture over 50 to 80 percent of its length. This estimate of rupture distance can be used to define the fault magnitude limit. Estimates of fault magnitudes have been made for many Western United States faults and are available and should be studied. It is essential to review previous geologic and seismological studies for the region to develop an understanding of the site's tectonic setting and seismic potentials.

Computation Of Recurrence Parameters The procedures are equally applicable to regional analysis or fault analysis. The subset of events assigned to the source zone of interest are used to calculate the Richter A and B coefficients, (Equation 5 in supporting material). This computation defines the earthquake recurrence as a line on a semilog plot. The linear segment is bounded by a maximum magnitude determined as discussed above and by a minimum magnitude below which the data becomes incomplete and not of interest. Typically, the value of B is about -0.9. The general earthquake recurrence is thus initially defined by the epicenter data. However, as will be shown in the following sections, two important elements are added: geologic slip data and characteristic magnitude.

Geologic Slip-Based Recurrence A procedure is shown in the supporting material for calculating recurrence based on the geologic slip rate data. Geologic slip rate data is available for a number of western faults. Such data is available from the CDMG Internet site. Once the seismicity is estimated from the historical data, the geologic data can be compared. The A and B values determined from the historical data should be adjusted based on the longer span geologic data. Should other studies be available, the results of these individual fault studies can be used here by adjusting the recurrence parameters.

Characteristic Magnitude Geologic data may show the presence of history of a characteristic event at some average return time. The seismicity defined by the historical data fails to capture this activity, so it is important to include it within the set of events developed for the fault. Once the size of the event and the effective average return time is defined, it becomes possible to include this in the analysis. Again, if studies with more advanced models are available to define temporal distributions, that data can also be used here.

Regional Seismicity Eastern US A regional study must be performed in which all of the historic epicenters are used with an attenuation relationship to compute site acceleration for all historic earthquakes for each zone. A regression analysis must be performed to obtain regional recurrence coefficients, and a map of epicenters plotted. The regional recurrence and available geologic data are to be used to compute the probability of site acceleration for randomly located events in the study area.

Fault Specific Seismicity Western US Where individual fault areas can be specified, individual subsets of the historic data are to be used in conjunction with geologic data to determine fault recurrence coefficients and characteristic magnitude events; these are to be used to compute the probability of site acceleration from individual fault sources. The total risk shall be determined for all faults specified. Confidence bounds are to be given on the site acceleration as a function of probability of not exceedance.

Local Site Amplification As a minimum, a one-dimensional wave propagation analysis shall be used to evaluate local site amplification.

Study Results The results of the seismicity study shall include the probability of site ground motion adjusted for local site effects. The structural design engineer may use either response spectra or time history techniques in the analysis of a structure. A set of site matched spectra or time histories shall be provided.

AVAILABLE AUTOMATED PROCEDURES FOR NAVY USE

Several computer programs has been developed to automate the site seismicity computation. The following programs are acceptable for Navy use:

Program SEI97

This program uses the NEHRP data base of computed acceleration on firm rock to determine approximate ground motion at a site. The data used was developed by USGS and CDMG and the program was written by NFESC. The only data required is the latitude and longitude of the site. This program is suitable for screening purposes. The data is used is based on a grid of 0.05 degree separation in California Utah and Nevada and 0.1 degree separation for the rest of the US. Because it interpolates between grid points it is not suited for use where there is significant close local faulting.

Program Seismic

This program was developed by NFESC to perform a detailed site study for a regional analysis or a fault specific analysis. program uses a formulation of a Monte Carlo simulation procedure, Ferritto (1994). This procedure uses the fault model and regional models discussed above, together with the recurrence procedure. As stated above, the A and B parameters combined with geologic slip rate data and characteristic magnitude form the basis for the recurrence function.
Once the recurrence function for a fault is defined, the magnitude distribution can be computed. The process is done for each fault individually. A list of 5,000 events representing the largest magnitudes expected to occur in 50,000 years is computed. For each magnitude, a fault break length is determined using data by Coppersmith (1991). A random epicenter location is selected along the fault. The fault break is then assigned to the random epicenter. Various distances are computed, such as epicentral distance, hypocentral distance, and closest distance of fault break to site. The choice of distance depends on the acceleration attenuation equation chosen by the user. Using the magnitude and separation distance, a site acceleration and standard deviation are

computed. A random acceleration is then determined. Associated with each acceleration is the causative event and distance. The process is repeated 5,000 times for each fault. The random fault data are then combined for a total site probability distribution. The procedure described above has the advantage that historical data are augmented with available geologic slip data. Where characteristic events are defined, they may be easily incorporated at the appropriate return time. The effective nonlinear recurrence function attempts to capture the temporal characteristics of the data without complex estimates of Markov or Bayesian parameters.

Program Equake

This program was written by NFESC to make a data base of spectra and time histories accessible. The data base of recorded accelerograms has been obtained and a program was prepared to search the record of accelerograms, given a desired magnitude event, epicenter-site distance, acceleration level, and soil condition, to determine the closest matching records. The program takes selected response spectra, and scales them, and then computes the mean and standard deviation spectra and the maximum envelope spectrum. The spectra are plotted either in tripartite form or in semilog form. The program also is able to scale, plot, and create files of time history accelerograms for use as input to dynamic finite element programs. Case studies were conducted to evaluate the procedure. Results compare favorably with results by others.

Program SHAKE

This program was funded by the National Science Foundation. It computes site amplification using one-dimensional wave propagation techniques. Input consists of specification of strain dependent shear modulus and damping parameters, a soil profile and an acceleration time history file. The program uses strain dependent linear material properties to determine site response.

Program Epic

The US Geological Survey National Earthquake Information Center, Denver, Colorado has produced EPIC, "The Global Hypocenter Data Base" (1992), a CDROM which contains parameters for more than 438,000 earthquake events. Seven world-wide and 12 regional earthquake catalogs were assembled to produce this data base, spanning a time period from 2100 BC through 1990. Useful data for the United States is generally constrained to the period when instruments were available to compute event magnitude. Each earthquake is detailed where data are available with date, origin time, location, magnitude estimates, intensity, and cultural effects.

APPLICATION

The criteria developed herein is intended to meet Navy needs subject to the following limitations:

- The exposure period or life of the structure is 50 years.

- Return times of events of interest are not appreciably longer than about one in a thousand years. This procedure is not intended to predict events such as the 10,000-year event with high accuracy.

Appendix

Technical Information Supporting Criteria

For

Computing Site Ground Motion

THE EARTHQUAKE MECHANISM

The United States is located on the North American plate, the western portion of which meets the Pacific plate. The interaction of these two plates is responsible for the high seismic activity in the Western United States. Plate tectonic theory has explained much of the geologic activity not only in the West but also in the Central and Eastern United States which can be also very destructive. Most seismic activity is located at plate boundaries and, therefore, boundaries are of considerable interest. There is general agreement on the close relationship between earthquakes and geologic faults. Plate motion causes stress in the earth's rock crust. Most tectonic earthquakes that cause major structural damage are associated with fracture of a fault. Earthquakes occur when the strength of the fault can no longer withstand the stress that has built up.

A fault is a rupture in the earth along which opposite faces have been displaced. The basic kinds of faults are defined as follows:

1. Strike Slip. Strike is the direction along a fault, and strike slip refers to displacement along this line. Right lateral or left lateral refers to the direction of movement of the opposite side when one faces the fault.

2. Normal. A normal fault refers to movement of one side of the fault away from the other, producing tension.

3. Thrust. A thrust fault refers to movement of one side toward or over the other side producing compression.

Most faults are combinations of strike slip and normal or thrust movement. The fault plane itself can be curved and blocks can be rotated relative to each other. The fault trace is the line of the fault along the ground surface. The strike of a fault is measured from north in degrees. The dip of a fault is used to measure the slope of the fault plane with the surface.

Estimates of the maximum size and frequency of earthquakes on a fault are based on the geologically determined slip rate and the historic record of ground deformation (where available), the seismic history of the fault and surrounding tectonic region, a geological evaluation of the tectonic setting, and empirically derived relationships between earthquake magnitude and fault length. When faults are considered, the assumption is commonly made that the creation of entirely new faults by an earthquake is unlikely (Krinitzsky, 1974). In the East, seismic activity is more complex and is associated with mid-plate movements particularly where faulting is not as evident.

EARTHQUAKE MAGNITUDE

Two factors of significance of importance in evaluating the earthquake potential associated with a fault are its capable magnitude and the strength of ground motion which can be produced. Factors that influence the selection of an earthquake limit magnitude are the length of geologic fault structure, the relationship of the fault to the regional tectonic structure, the geologic history of displacement along the structure, and the seismic history of the region. In a probabilistic analysis the maximum magnitude represents the upper limit event that a fault is capable of generating. Earthquake magnitude can be related to length of fault for shallow depth earthquakes. Data have been plotted by Seed, et al. (1969), Krinitzsky (1974), Housner (1965), Mark and Bonilla (1977), and Tocher (1958) to relate magnitude to fault rupture length. It is important to note that in some regions, correlations of these types are of little value since many of the important geologic features can be deeply buried by weathered materials. More recent data by Coppersmith (1991a and 1991b) are shown in Figures 1 and 2.

Magnitude as measured on the Richter scale is calculated from a standard earthquake, one which provides a maximum trace amplitude of 1 μm on a standard Wood-Anderson torsion seismograph at a distance of 100 km. Magnitude is the $\log_{10}$ of the ratio of the amplitude of any earthquake at the standard distance to that of the standard earthquake. Each full numeral step in the scale (two to three, for example) represents an energy increase of about 32 times. Experience with past earthquakes is presently the only useful basis for relating fault length and motion to magnitudes of associated earthquakes.

A useful insight into the relationship between earthquake magnitude and length of observed fault slippage is presented by Iida (1965). He groups faults of all types and shows a wide spread of points for which upper and lower boundaries are drawn. Iida's wide spread of values should be kept in mind when one considers the linear relationships that have been suggested by numerous authors. Fault movements below a magnitude of 5 are usually contained in the subsurface. If active fault movement is found at a site, even small movement, it should be viewed as evidence for an earthquake capability of greater than 5 (Krinitzsky, 1974). It is important to note the spread in the data and Krinitzsky (1974) concludes, "Any fault break in competent rock, no matter how small, should be taken as indicative of the capability for at least a 5.4 earthquake." It is important that the local seismic history and the behavior of other analogous faults be considered. Consideration should be given to the possibility of not identifying all the faults in a region that may be active. This is especially true in the Central and Eastern United States. To account for this a "floating earthquake" (one that may be assumed capable of occurring anywhere in the region) should be considered, Krinitzsky, 1974.

GEOLOGICALLY DETERMINED SLIP RATES AND RECURRENCE

The offset of distinctive rock units evidences the rate of fault movement within fairly wide bounds. Commonly these offsets average the rate of movement over millions of years, and sudden slip cannot be distinguished from creep. For example, data for the San Andreas fault suggest an average slip rate of 1 to 2 cm/yr over the last 20 million years. But to predict movements in the immediate future, the most recent hundreds to thousands of years are the most important, Wesson, et al., (1975). The history and rate of fault movement have been estimated and compiled by the California Division of Mines and Geology and are available over the Internet.

Wallace (1970) explains the approach that has been used by others including Lamar, et al. (1973). The recurrence interval at a point can be estimated by:

$$R_x = \frac{D}{S - C} \qquad (1)$$

where: D = displacement per seismic event
S = long-term slip rate
C = tectonic creep rate
S - C = average seismic slip rate

Lamar, et al. (1973) present the following quoted discussion:

> "The following assumptions are made: (1) Slip on faults occurs incrementally during earthquakes and will continue at the same rate as that determined from geodetic data and offset of geologic units. (2) Elastic strain accumulates between earthquakes; the displacement during an earthquake represents the release of this accumulated elastic strain. (3) Tectonic creep is aseismic slip which reduces the accumulation of elastic strain available for release during earthquakes. ...Recurrence intervals determined by [Equation 1] represent a long-term average; there is however, evidence of significant local (Ambraseys, 1970) and worldwide (Davies and Brune, 1971) time variations in the level of seismic activity."

For most faults, creep cannot be evaluated. Therefore, as an expedient, Equation 1 is simplified as:

$$R_x = \frac{D}{S} \qquad (2)$$

Equation 2 is appropriate when the rupture length is large compared to the distance of the site to the fault. When this is not the case, Equation 2 is multiplied by the ratio of length of rupture to total fault length to account for the spatial distribution.

Since the early work of Wallace (1970), more emphasis has been placed on use of geologic data. The historic seismicity record in the United States and other areas is generally too short to fully define the recurrence of particular individual faults for low probability events. Fault slip rates derived from geologically defined intervals afford the opportunity of spanning several cycles of large earthquakes on a fault. Coppersmith and Youngs (1990 a and b) note that the best geologic units for assessing slip rate for recurrence purposes are late-Quarternary or Holocene units. Assessing slip rates over relatively young units will avoid averaging out long-term changes in the slip rate from regional changes in tectonic stress. Determination of slip rate is an area for seismologists; fortunately more west coast data is becoming available to aid the engineer, Wesnousky (1986) and Working Group On California Earthquake Probabilities (1995).

SLIP RATE AND SEISMIC MOMENT

Seismic moment has been used in conjunction with slip rate. Seismic moment, M_o, is a means of describing the size of an earthquake in terms of physical parameters:

$$M_O = \mu A_r D \qquad (3)$$

where: μ = rigidity or shear modulus (taken as 3×10^{11} dyne/cm^2)
A_r = rupture area on the fault plane
D = average displacement over slip surface

The total seismic moment rate can be estimated using the above formulation substituting the total fault plane area and the average slip rate along the fault instead of the displacement. Thus, the seismic moment rate provides a link between geologic data and seismicity. Seismic moment rates determined from slip data can be compared with seismic moment rates based on seismicity data, Youngs and Coppersmith, (1985).

Seismic moment, M_o, can be related to magnitude, m, as follows:

$$\log M_o = C\,m + d \qquad (4)$$

Hanks and Kanamori (1979) report that c = 1.5 and d = 16.1 in California. The moment magnitude, m, is considered equivalent to local magnitude when in the range of 3 to 7 and to surface wave magnitude when in the range of 5 to 7.5.

EPICENTER DATA BASE

The US Geological Survey National Earthquake Information Center, Denver, Colorado has produced EPIC, "The Global Hypocenter Data Base" (1992), a CDROM which contains parameters for more than 438,000 earthquake events. Seven world-wide and 12 regional earthquake catalogs were assembled to produce this data base, spanning a time period from 2100 BC through 1990. Useful data for the United States is generally constrained to the period when instruments were available to compute event magnitude. Each earthquake is detailed where data are available with date, origin time, location, magnitude estimates, intensity, and cultural effects.

A computer program, EPIC, is available for searching the CDROM. EPIC makes data available to information users via a user-defined search request. The request determines which steps are necessary to produce the desired output. An automated plotting package that produces seismicity maps in multicolor or monochrome is incorporated into the EPIC software. The data to be mapped are extracted from the selected data and plotted in a global or regional format. The availability of the CDROM data base of epicenters and EPIC software greatly facilitates creation of the historical epicenter subset required for use with automated site seismicity analysis tools. Details are presented in the EPIC user's manual, which will not be repeated here.

A number of data fields for some events are unfilled because the information is not available. Information on cultural effects, intensity, and other phenomena associated with the event has been included for earthquakes in the United States. This information has sometimes been entered for non-United States earthquakes, particularly since May 1968, although significant gaps still exist. The quality of epicenter determinations varies significantly with the time period studied. Before 1900, locations are usually noninstrumentally determined and are given as the center of the macroseismic effects. Most instrumental epicenters prior to 1961, excluding local earthquakes in California, were located to the nearest 1/4 or 1/2 degree of latitude and longitude. Reliable information on the quality of many epicenter determinations is lacking. Beginning in 1960, epicenters have been determined by computer, and the accuracy is generally better. However, although stated to tenths or hundredths of a degree, the location accuracy is usually a few tenths of a degree. Since May 1968, the latitude and longitude values for most events have been listed to three decimal places. This precision is not intended to reflect the accuracy of the location of events except for local California earthquakes and special epicenter determinations. Where several sources have determined an epicenter for the same earthquake, one solution has been designated as the most reliable. Usually it is the source believed to contain the best data set for the earthquake. In some cases, data from two sources were combined to provide a more complete record. Magnitudes from a number of different sources are included in the earthquake data file. Gutenberg and Richter (1954) and Richter (1958) discuss the development of the magnitude scale. Many magnitudes published by Gutenberg and Richter (1954) were later revised by Richter (1958). The revised magnitudes are used in the file even though the source is identified as Gutenberg and Richter (1954). The concept of earthquake magnitude is not restricted to one value. Several definitions are possible, depending on which seismic waves are measured. Three different magnitude scales, body wave (MB), surface wave (MS), and local (ML), are distinguished in this file. In addition, another data field, other magnitude, was included when it was unclear which scale was used. Recent earthquakes are being defined by moment magnitude. Richter (1958) and other modern seismology references provide detailed discussions on the topic of magnitude determination. The different scales do not give exactly comparable results, and different values frequently are given for the same earthquake. It is common practice to average the individual magnitudes from different stations to get a more uniform value within each scale (MB, MS, and to a lesser extent ML).

In general, the file contains earthquakes of magnitude less than 4.0 only for the United States region and for areas within dense seismic station networks. However, no claim is made for the statistical homogeneity of these events. Inclusion of earthquakes of magnitude 4.0 to 5.0 also is influenced by the proximity of seismic stations to the source or epicenter. A maximum intensity is listed for many of the earthquakes. Each is assigned according to the Modified Mercalli Intensity Scale of 1931. Some of these values have been converted from reported intensities on other scales.

A period of demonstrated quiescence over a geological time period indicates inactivity of the fault and probable continued inactivity. However, inactivity over a period of historic recording (50 to 100 years) does not imply future inactivity. Rather, it may point to a region which is locked and through which a major fault rupture may propagate. A number of earthquakes producing damage in southern California occurred on faults lacking historic activity. Caution must be exercised to recognize that the limitations of an incomplete data base when extrapolating to return periods greatly exceeding the length of the period of recorded data. Furthermore, aftershocks must be distinguished from main shocks. An area having recently undergone a large event releasing strain built up for hundreds or thousands of years is probably safe against a large release in the near future. Thus, a recent large event on a fault might actually indicate safety in the immediate future, rather than an indication of increased activity. A single event by itself cannot give an accurate measure of return time.

ESTIMATING EARTHQUAKE RECURRENCE

A fundamental step in the estimation of seismic hazard is the definition of recurrence interval of possible earthquakes as quantification of site exposure. In 1954 Guttenberg and Richter developed an exponential frequency magnitude relationship:

$$\log N(m) = a - b\,m \qquad (5)$$

where: $N(m)$ = cumulative number of earthquakes greater than m
a = constant
b = constant

Equation 5 can be written in the form of an exponential distribution:

$$N(m) = \exp(a - b) \qquad (6)$$

where: $\alpha = a \ln(10)$
$\beta = b \ln(10)$

A lower bound, m_l, can be selected as an arbitrary reference point. The following can be developed:

$$N(m) = N(m_l) \exp(-\beta(m-m_l)) \qquad (7)$$

where: m_l = arbitrary reference magnitude

Equations 5, 6, and 7 are constrained by an upper limit magnitude associated with the capability of a specific fault to generate such an event based on the fault's length and maximum rupture possible. The physical limitations of an upper limit truncate the magnitude distribution.

To estimate frequency with less error, a magnitude frequency relation in the form of:

$$\log_{10} N(m) = a_o + b_1 m + b_2 m^2 \qquad (8)$$

has been used. This quadratic form has an advantage of not overestimating the occurrence of large events and avoids the discontinuity of the function from a truncated linear frequency distribution.

Another generalized formulation of the Guttenberg-Richter relation is of the form:

$$\ln N(m) = A - B \exp(\alpha m) \qquad (9)$$

Coppersmith and Youngs (1990) report that recent geologic studies of late quaternary faults strongly suggest that the exponential recurrence model is not appropriate for expressing earthquake recurrence on individual faults. Their studies suggest many individual faults tend to generate essentially the same size or characteristic earthquakes having a relatively narrow range of magnitudes at or near the maximum. This conclusion is based upon evaluating the amount of displacement per event for studies of the Wasatch and south-central San Andreas faults. This implies that earthquake recurrence does not conform to an exponential recurrence model but rather one that has a variable b value. The type of geologic recurrence interval data developed for the Wasatch and San Andreas faults are not generally available for most faults in the Western United States.

Youngs and Coppersmith (1985) note that when geologically derived recurrence intervals for characteristic earthquakes are compared with relationships derived from seismicity data, a marked mismatch occurs. The characteristic earthquake was found to include a band of events of about one-half magnitude width. For events less than the characteristic event magnitude, the exponential recurrence behavior was found to be a satisfactory representation. The increment between the minimum characteristic magnitude and the portion of the recurrence curve showing exponential behavior at recurrence rates greater than the rate for characteristic events is about one magnitude in width. The magnitude range showing nonexponential behavior is about 1.5

magnitudes in width. Figure 3 shows the generalized function. To simplify application, Δm_c is 0.5 magnitude units, m' is set at $m^u - \Delta m_c$, and the value of n (m^c) is equal to n (m'-1).

EARTHQUAKE EVENT RETURN TIME

The Poisson process has been used to describe earthquake occurrences and represents a basic model with only a single parameter to define. A Poisson process is a continuous time, integer-valued counting process with stationary independent increments. This means the number of events occurring in an interval of time depends only on the length of the interval. The probability of an event occurring in the interval is independent of the history. The probability distribution of the number of earthquakes is given by:

$$P_N(n, \lambda t) = \frac{e^{-\lambda t}(\lambda t)^n}{n!} \qquad (10)$$

where: P_N = probability of occurrence of n events of a given magnitude range

λ = mean rate of occurrences per unit of time t

The expected value of the numbers of earthquakes in time t is:

$$E(t) = \lambda t \qquad (11)$$

A characterization of the Poisson process is that the time between events is independent, identically and exponentially distributed with a constant rate of occurrence, λ. The density function of the time between events is:

$$f(t) = \lambda e^{-\lambda t} \qquad (12)$$

A consequence of Equation 12 is the hazard rate for the Poisson process is constant. In general, the hazard rate is defined as:

$$h(t) = \frac{f(t)}{1-F(t)} \qquad (13)$$

where F(t) is the cumulative distribution function of the time between events. The quantity h(t)dt is the conditional probability of an event occurring in (t, t+dt) given there are no events in the interval (0,t). For the Poisson process,

$$h(t) = \frac{\lambda e^{\lambda}}{1 - (1 - e^{\lambda})} = \lambda \qquad (14)$$

The constant hazard rate implies that the occurrence of an event in (t, t+dt) is independent of the time since the last event. This means that whether an earthquake of size m just occurred or whether there is a significant gap in events, the probability of an event occurring is independent of past history. Physically, the energy released during event m does not affect the reservoir of stored energy available for subsequent events.

A significant advantage of the Poisson process is that it is based only on the epicenter data base. Thus, when additional information is lacking, it may be applied. Other models require additional parameters which may not be available, and will require substantial effort to acquire.

An improvement over the Poisson distribution is the Weinbull distribution suggested by Chou and Fisher (1975). A Markov or semi-Markov process can be defined as a process in which the occurrences of earthquakes make transitions from one range of earthquake magnitude to each of several other ranges. The transitions are probabilistic and have a one-step memory and the probability of moving to a given magnitude depends on the preceding magnitude. A semi-Markov process is also characterized by a probabilistic holding time between successive transitions. The probability that the holding time between two successive earthquakes is equal to a given value depends on the magnitude of the two events. The semi-Markov process is consistent with the physical understanding of the earthquake process. That process consists of a gradual uniform accumulation and periodic release of significant strain energy within short periods of time following an earthquake of large magnitude. The occurrence of another such sized event at the same location is less likely. As the time without occurrence of a large magnitude event increases, so does the probability of the occurrence of such an event. The size of the next large event and the holding time to that event are influenced by the amount of strain energy released in the previous event and the time during which strain energy has been accumulating.

Definition of the semi-Markov model requires specification of the most recent earthquake for a fault and the elapsed time since that event for various magnitude levels. Transition probabilities for each magnitude to other magnitudes must be specified. A probability distribution of holding times between the occurrence of two successive events must be determined. The exposure time or period of interest must be specified. Woodward Clyde (1982) describes development of such a model that uses a Poisson process for events below a specified magnitude and a semi-Markov process for events above that level. This model requires a Bayesian approach for parameter estimation. The ability to use this class of model depends on the ability to quantify input data. The Bayesian approach will not be discussed because practical limitations exist in obtaining required data needed for use. The Markov process utilizes subsets of the epicenter data base for earthquake occurrences. This analysis of windows into the data requires a large catalog of events which are often not available. For this reason, semi-Markov models incorporate other techniques.

The Poisson process has a distinct advantage in its ability to be used with available data to characterize its single parameter. The independence assumptions associated with the Poisson process do not permit it to characterize the underlying physical process of strain buildup and release. The time dependence feature is lacking. It was found to be unconservative when a long gap occurred since the last event occurred on a fault. Cornell and Winterstein (1988) give an excellent evaluation of the limitations and applicability of the Poisson model. They studied a broad set of models with temporal and magnitude dependence, including time and slip predictable models. They considered agreement acceptable for engineering hazard studies when results agreed within a factor of three for a 50-year time window and magnitude levels with annual exceedance probabilities of 0.001 or less. According to Cornell and Winterstein (1988):

> "The Poisson model has been commonly used for several reasons. These include: (1) some successful comparisons of its predictions with observations..., (2) rather broad acceptance that, lacking evidence to the contrary, the model is not unreasonable physically (especially for the less-than-the-largest events that may govern hazard); and, more formally, (3) the fact that the sum of non-Poissonian processes may be approximately Poisson. But perhaps most importantly, it is the simplest model that captures the basic elements of the problem. ...Significantly, these parameters of the standard hazard model are those that the engineering seismologist commonly estimates and is therefore best prepared to specify. Should an alternative model be considered, questions arise, first, as to which alternative model should be considered and, second, as to how in practice to estimate both the additional model parameters and the initial conditions (e.g., size and time of the last significant event) upon which non-Poissonian predictions may depend. Therefore, the practical application on non-Poissonian models requires much more detailed knowledge of specific tectonic features. If the engineering conclusions are not substantively different, the implied effort may not be justified. Cases in which the Poisson estimate is insufficient are limited practically to those in which the hazard is controlled by a single feature for which the elapsed time since the last significant event exceeds the average time between such events. Moreover, this situation creates a problem only if there is reason to believe that the fault displays strongly regular, "characteristic time" behavior. In particular, the Poisson estimate will generally be adequate if the mean interevent time between significant events exceeds either the seismic "gap" (elapsed time since the last such event) or the length of the historical record, whichever is less. For strongly regular earthquakes, the mean gap length under random entry is roughly half of the mean interevent time; therefore, this gap with higher than Poisson hazard may be rather unusual in engineering design practice.
>
> Finally, in many practical situations, two or more features will be important hazard contributions at a particular site. In these cases, the combined hazard is better estimated by the Poisson model than is the hazard from any single feature."

Lomnitz (1989), in a discussion of the Cornell and Winterstein (1988) paper, makes the following comment:

> "Cornell and Winterstein found that the fit to the Poisson model improved as the number of discrete sources increased. If there are two or more faults, "the combined hazard is better estimated by the Poisson model than is the hazard from any single feature." This result is not altogether unexpected. An elegant theorem... proves that the sum of any number of random point processes tends to a Poisson process. The larger the number of arbitrary component processes, the better the Poisson fit.
>
> Hence, it is not quite fair to state that the effects of temporal and magnitude dependence "are ignored in the conventional Poisson earthquake model" (Cornell and Winterstein, 1988). The model is not that unsophisticated. The Poisson process is a limiting process for the sum of many point processes - all of which exhibit time and magnitude dependence!
>
> For example, the earthquake hazard in North China is governed by a few large faults, both on land and in the Gulf of Bo, plus an unknown number of small faults. The capital city of Beijing, which appears to be somewhat removed from the major faults, may be adequately planned on the basis of a Poissonian earthquake hazard (which in effect means that the ground conditions dominate the hazard). But I would be concerned about applying the same criterion to a site on the Tangshan Fault - event though a significant earthquake occurred on that fault as recently as 27 July 1976."

For engineering hazard studies using the historical data base and available slip data, a Poisson model may be used as a starting point. Geologic data should then be used to adjust recurrence data computed from the historical data base. Characteristic event data can easily be incorporated, and this should be done where required. This represents an "engineering" solution for a range of studies where the exposure time is 50 years or less and the annual risk levels of interest are in the range of 0.001. Studies where the annual risk range is 0.0001 require more detailed analysis.

GROUND MOTION ATTENUATION

This section will review several ground motion attenuation equations which are used to determine levels of acceleration as a function of distance from the source and magnitude of the earthquake. The increased installation of strong motion data recording equipment has provided an accumulation of earthquake records. Correlations have been made of peak acceleration with distance for various events. These equations allow us to estimate the ground motion at a site from a specified event and the uncertainty associated with the estimate. This estimation is a key step in any seismic hazard analysis. There are a number of attenuation equations that have been developed by various researchers and are considered acceptable. As the data set expands and more data points are available, agreement among researchers improves.

Joyner And Boore Joyner and Boore (1988) developed an attenuation equation based on a regression analysis of a carefully selected set of events. The events are restricted to moment magnitude, M, greater than 5 and less than 7.7 and shallow fault rupture. Their equation is:

$$\begin{aligned} \log y &= a + b(M - 6) + c(M - 6)^2 + d(\log(r)) + k\,r + s \\ r &= (r^2 + h^2)^{1/2} \end{aligned} \qquad (15)$$

where a, b, c, d, k, s, and h are constants.

Crouse, et al. Crouse, et al. (1984) developed the following equation for peak horizontal acceleration and horizontal pseudovelocity response at 5 percent damping. It was developed from data recorded at deep soil sites (generally greater than 60 m in thickness) during shallow crustal earthquakes in southern California (Crouse 1984, 1987; Vyas, et al., 1988):

$$\ln y = a + b\,M_S + c\,M_S^2 + d\,\ln(r + 1) + k\,r \qquad (16)$$

where: y = peak horizontal acceleration (gal) or horizontal pseudovelocity response (cm/s)
M_S = surface-wave magnitude
r = closest distance (km) from rupture surface to recording site

The values of a, b, c, d, and k are constants. Both horizontal components were used so that the values of y predicted by Equation 16 correspond to the randomly oriented horizontal component.

Sadigh, et al. Sadigh, et al. (1986) developed an equation for peak horizontal acceleration and horizontal pseudoacceleration response at 5 percent damping from data from the Western United States supplemented by significant recordings of earthquakes at depth less than 20 km from other parts of the world. Both horizontal components were used:

$$\ln y = a + b\,M + c_1\,(8.5 - M)^{c2} + d\,\ln\,[r + h_1 \exp\,(h_2 M)] \qquad (17)$$

where: y = peak horizontal acceleration (g) or horizontal pseudoacceleration (g)
M = moment magnitude
r = the closest distance (km) to the rupture surface
a, b, c_i, d, and h_i are constants

The constant values were derived for strike-slip earthquakes. To obtain estimates for reverse-slip events, the strike-slip estimates should be increased by 20 percent. Sadigh, et al. (1989) used additional earthquake data through 1988 to develop a set of coefficients for short-period horizontal ground motion at rock sites in reverse-slip earthquakes. Data from both horizontal components were used in developing the equations, and the results apply to reverse-slip earthquakes. The results should be reduced by 17 percent to give estimates for strike-slip events and by 9 percent to give estimates for reverse-oblique slip events. The shape of response spectra computed from Equation 17 does not change with distance.

Donovan and Bornstein Donovan and Bornstein (1978) developed the following equation for peak horizontal acceleration from the Western United States data. Both horizontal components were used:

$$y = a \exp(b M) (r + 25)^{d}$$

$$a = 2{,}154{,}000(r)^{-2.10}$$

$$b = 0.046 + 0.445 \log(r)$$

$$d = 2.515 + 0.486 \log(r) \qquad (18)$$

where: y = peak horizontal acceleration (gal)
M = any magnitude
r = distance (km) to the energy center, default at a depth of 5 km

Campbell Campbell (1987, 1989) developed equations for estimating peak acceleration, peak velocity, and pseudovelocity at 5 percent damping. He used a worldwide data set including earthquakes as recent as 1987 based on the following criteria:

> "(1) the largest horizontal component of peak acceleration was at least 0.02 g; (2) the accelerograph triggered early enough to record the strongest phase of shaking; (3) the magnitude of the earthquake was 5.0 or larger; (4) the closest distance to seismogenic rupture was less than 30 or 50 km, depending on whether the magnitude of the earthquake was less than or greater than 6.25; (5) the shallowest extent of seismogenic rupture was no deeper than 25 km."

Records from instruments on the abutments or toes of dams were excluded, as were records from "hard-rock" sites and shallow-soil sites, which were defined as sites with 1 to 10 m of soil overlying rock. Campbell's (1989) equation is:

$$\ln y = a + bM + d \ln [r + h_1 \exp(h_2 M)$$

$$+ q F f_1 \tanh [f_2 (M + f_3)] + g_1 \tanh(g_2 D) + \sum_{i=1}^{3} l_i K_i$$

where:

y = ground motion parameter of interest, the vertical component or the mean of two horizontal components.

M = surface wave magnitude M_S if both local magnitude M_L and M_S are greater than or equal to 6.0 or M_L if both M_S and M_L are less than 6.0.

r = the shortest distance (km) to the zone of seismogenic rupture, identified from spatial distribution of aftershocks, from earthquake modeling studies, from regional crustal velocity studies, and from geodetic and geologic data.

D = depth to basement rock (km).

F and K are constants

Idriss Idriss (1985, 1987) developed the following for the randomly oriented horizontal component of peak horizontal acceleration:

$$\ln y = \ln a + d \ln(r + 20) \qquad (20)$$

where: y = peak horizontal acceleration (g)

M = surface-wave magnitude for M greater than or equal to 6 and local magnitude otherwise.

r = closest distance (km) to the source for M greater than 6 and hypocentral distance otherwise.

a and d are constants

Idriss proposed that peak acceleration be used to scale the response spectral shapes for different site conditions with magnitude- and period-dependent correction factors. The shape of response spectra computed by Idriss' method does not change with distance.

Comparison Of Equations According to Joyner and Boore (1988):

> "....to properly compare the different relationships, adjustments must be made for the different definitions of distance. [Figure 4] compares peak horizontal acceleration for the randomly oriented horizontal component at magnitude 6.5 as estimated by Donovan and Bornstein (1978), Joyner and Boore (1988), Idriss (1987), and Campbell (1989). The definition of distance used in [Figure 4] is the closest distance to the vertical projection of the rupture on the surface of the earth. The curves of Donovan and Bornstein and Campbell were adjusted assuming a source depth of 5 km. The curve shown for Idriss is that for deep soil sites. The curve shown for Campbell is that for strike-slip earthquakes recorded at free-field sites.
>
> At short distances, where it matters the most, the different relationships agree to within a fraction of the uncertainty of an individual estimate as given by any of the authors. This suggests that the short-distance estimates at magnitude 6.5 are controlled by the data. The differences at large distances are not of much practical importance."

Figure 4 gives the same comparison for magnitude 7.5. The agreement at short distance is not as good as at magnitude 6.5, reflecting the scarcity of data points, but it is within the uncertainty of an individual estimate. From Figure 4, the Donovan and Bornstein equation yields an almost upper bound and is a conservative estimate.

A PROCEDURE FOR COMPUTING SITE SEISMICITY

As noted by Coppersmith (1991), many elements of seismic source characterization depend on the tectonic environment. In the Western United States, the tectonic environment is such that earthquakes are associated with known faults. However, in the Eastern United States, the causative geologic structures are generally not known. A seismic model must be based on the knowledge of the local area. It can consist of an area source zone for eastern sites or a detailed fault definition region for western sites.

In the Western United States, it is recognized that large earthquakes are associated with faults. For a magnitude 8 event, a rupture of 200 miles is required to release that level of energy. A 200-mile fault exhibits visual evidence of its existence and is unlikely to remain undiscovered. It is possible for lower magnitude events that require considerably less fault rupture to occur on faults lacking recent evidence of activity, or on faults that have not been identified. Where faults are identified as sources, the area contained within the source zone is defined to have relatively uniform seismic potential in terms of maximum magnitude and event recurrence. A fault is modeled as a line source encompassing a distance or region surrounding the fault, such that the activity of this region can be associated with events on the fault. Where a fault exhibits variations of activity along its length, it can be divided into subelements containing regions where activity is uniform.

For the procedures developed herein, a fault segment can be modeled by two line segments defined by three points. The events to include or associate with the fault are defined by specification of a distance from the fault line, such that all those events within the distance are grouped with the fault. Alternatively, a region can be designated by four points to bound the fault. Again, note a fault can be divided into pieces where activity or geometry so dictates.

In the Eastern United States, faulting may not be readily identifiable. Source zones are specified as regions where a zone of like seismicity is evident. The regional geology and tectonics assist in defining the source zone boundaries. A source zone is defined as a region of uniform seismicity, such that an event is equally likely to occur in any portion of the zone. This is characterized by the concept of a "floating earthquake," an event that can occur anywhere in the zone.

In the development of a site model, it is important to keep in mind that an equivalent representation of a region is being created by a series of fault line segments or source zones. The seismicity must be captured in terms of its spatial location and in terms of the level of activity. Assignment of events to one fault source as opposed to another increases that fault's contribution to the estimation of event recurrence. It is important to capture all the seismicity. For faulting conditions where there are a number of parallel elements, it may not be easy to separate which events are associated with which fault. Consideration must be given to the dip of the fault in assigning events, since the epicenter for a sloping fault can actually occur in a number of kilometers away from the surface trace of the fault. The large majority of strike slip faults have steep dips of 70 degrees or greater. On the other hand, thrust faults generally have dips much less than this, generally in the range of 45 to 60 degrees. For the cases where a fault is close to a site (within 10 miles), special considerations should be given to the location of the fault line segments that define the fault model. If the fault dips toward the site, the actual epicentral distance may be closer to the site than the surface trace of the fault. For faults at greater distances, the difference becomes less significant.

Once a fault or region has been defined as a seismic source, the maximum earthquake magnitude must be defined. In a previous section, a plot was shown relating fault rupture length to magnitude. The length of a fault can be estimated from maps. An assumption can be made that a fault will rupture over 50 to 80 percent of its length. This estimate of rupture distance can be used to define the fault magnitude. Estimates of fault magnitudes have been made for some Western United States faults. It is essential to review previous geologic and seismological studies for the region to develop an understanding of the site's tectonic setting and seismic potentials.

Computation Of Recurrence Parameters The procedures discussed in this section are equally applicable to regional analysis or fault analysis. The subset of events assigned to the source zone of interest are used to calculate the Richter A and B coefficients, Equation 5 above. This computation defines the earthquake recurrence as a line on a semilog plot. The linear segment is bounded by a maximum magnitude determined as discussed above and by a minimum magnitude below which the data becomes nonlinear. Typically, the value of B is about -0.9. The general earthquake recurrence is thus initially defined. However, as will be shown in the following sections, two important elements are added to geologic slip data and characteristic magnitude.

Geologic Slip-Based Recurrence A procedure were presented above for calculating recurrence based on the geologic slip rate data. Once the seismicity is estimated from the historical data, the geologic data can be compared. The procedure allows the user to adjust the A and B values from the historical data to include information based on the longer span geologic data. Should other studies be available, the results of these individual fault studies can be used here by adjusting the recurrence parameters.

Characteristic Magnitude As discussed above, geologic data may show the presence of history of a characteristic event at some average return time. The seismicity defined by the historical data fails to capture this activity, so it is important to include it within the set of events developed for the fault. Once the size of the event and the effective average return time is defined, it is possible to include this in the analysis. Again, if studies with more advanced models are available to define temporal distributions, that data can be used here.

Computational Procedure Various approaches were presented above to determine the probability of earthquake occurrence. As shown above, various amounts of data are required, some of which are beyond the scope of an engineering investigation. A new approach was taken in the formulation of a Monte Carlo simulation procedure, Ferritto (1994). The procedure uses the fault model and regional model discussed earlier, together with the recurrence procedure. As stated above, the A and B parameters combined with geologic slip rate data and characteristic magnitude form the basis for the recurrence function.

Once the recurrence function for a fault is defined, the magnitude distribution can be computed. The process is done for each fault individually. A list of 5,000 events representing the largest magnitudes expected to occur in 50,000 years is computed. For each magnitude, a fault break length is determined using data by Coppersmith (1991). A random epicenter location is selected along the fault. The fault break is then assigned to the random epicenter. Various distances are computed, such as epicentral distance, hypocentral distance, and closest distance of fault break to site. The choice of distance depends on the acceleration attenuation equation chosen by the user. Using the magnitude and separation distance, a site acceleration and standard deviation are computed. A random acceleration is then determined. Associated with each acceleration is the causative event and distance. The process is repeated 5,000 times for each fault. The random fault data are then combined for a total site probability distribution. The procedure described above has the advantage that historical data are augmented with available geologic slip data. Where characteristic events are defined, they may be easily incorporated at the appropriate return time. The effective nonlinear recurrence function attempts to capture the temporal characteristics of the data without complex estimates of Markov or Bayesian parameters.

Automated Procedure A computer program has been developed to automate the site seismicity computation. Ferritto (1994) presents the details and user's manual.

EARTHQUAKE RESPONSE SPECTRA AND TIME HISTORIES

In earthquake engineering it is important to be able to determine the magnitude of maximum response of a structure. This has given rise to the response spectra technique. An elastic single-degree-of-freedom, spring-mass-damper system can be analyzed and its time history of displacement calculated to determine relative displacement between the mass (the structure) and the excited base (the ground). Relative velocity and relative acceleration may also be calculated. However, of primary interest for engineering applications is the maximum absolute values of structure relative-displacement, structure relative-velocity, and absolute structure acceleration. These values SD, SV, SA are functions of the critical damping. Plots of SD, SV, SA versus the undamped natural period of vibration and for various fractions of critical damping are called response spectra. For earthquake-like excitations that are not strictly harmonic excitation, an engineering assumption is made that the response is approximately harmonic. The term "pseudo" is used to recognize the assumptions made concerning small damping and harmonic motion. Thus, SD, PSV, PSA, and T make up a set of data; knowing any two makes it possible to determine the other two. This unique relationship makes it possible to plot response spectra in tripartite form. The response spectra shows the response of a single-degree-of-freedom system (structure) as a function of damping of the system and period for the given input acceleration. The response spectrum is usually used in structural engineering with the modal analysis technique. This approach determines the eigenvalues and mode shapes for a number of the modes of the structure, and using this and the spectra determines the loading to be applied to each significant mode of the structure included in the analysis.

An alternative structural analysis technique directly uses the ground motion acceleration time history in a step by step incrementation process. Time history records of actual earthquakes are available from a number of sources. These may be scaled and used when required for time history input of ground motion. Care is needed in selection since many records are recorded in structures that may influence the recording. Also, the region around the site may influence the site response. Only true ground motion recordings should be used. The propagation of seismic waves is influenced by the local geology and soil conditions. The depth of soil overlaying bedrock affects the period of vibration of the ground. This establishes a fundamental soil frequency of particular importance on soil-structure interaction. Further, this is a factor in determining the frequencies of waves filtered out by the soil, thus directly affecting the time history record. Historical records should be chosen to reflect the actual site soil conditions at the site under investigation.

SITE-MATCHED SPECTRA

The data base of strong motion records can be a useful source of seismic data. Records may be selected to represent seismologic, geologic, and local site conditions. Selection is complicated by a number of factors. Ideally, the records should be selected to match source-site transmission path, source mechanism, and local site conditions. These are not readily quantifiable. Thus, reliance is made on earthquake magnitude site acceleration level, site classification, and duration of motion. Judgment is an important factor in selecting and scaling records.

Ferritto (1992) describes a desktop computer program for computing optimized earthquake time histories and response spectra. The program has the data base of about 1,000 records provided by the National Oceanographic and Atmospheric Administration. The user may select specific records and obtain time histories and spectra or may specify a ground acceleration level, site distance, and magnitude and the program will search the data base and provide the user with a list of the closest matching records. The user may then combine a number of spectra and obtain average, average plus one standard deviation, and envelope spectra.

It is suggested that site-matched groups of spectra be used to develop the mean and mean-plus-1-standard-deviation spectra. These should be compared with standard spectral shapes and typical results for soft, intermediate, or rock sites to denote regions where the spectra may be deficient. This is particularly important for Eastern sites since the spectra are recorded in the West. Significant variations in attenuation have been noted between Western and Eastern ground motion.

Two alternative procedures used to determine site specific ground motion are as follows.

Surface Motion This technique utilizes attenuation relationships based on surface motion. The computed motion is then used as a scaling value for the response spectra. The specific response spectrum may be based on a group selected for similar site properties or a spectral shape determined by researchers to be applicable to specific site conditions.

Bedrock Motion This technique utilizes an attenuation relationship based on bedrock motion. The motion may be brought to the surface either from empirical data or by use of wave propagation computation programs. An automated-analysis technique, widely used today for treating horizontal soil layers, has been developed by Schnabel, Lysmer, and Seed (1972), based on the one-dimensional wave propagation method. This program, SHAKE, can compute the responses for a given horizontal earthquake acceleration specified anywhere in the system. The analysis incorporates nonlinear soil behavior, the effect of the elasticity of the base rock, and variable damping. It computes the responses in a system of homogeneous viscoelastic layers of infinite horizontal extent, subject to vertically traveling shear waves. The program is based on the continuous solution of the wave equation adapted for use with transient motions through the Fast Fourier Transform algorithm. Equivalent linear soil properties are obtained by an iterative procedure for values of modulus and damping compatible with the effective strains in each layer. The following assumptions are made:

1. The soil layers extend infinitely in the horizontal direction.

2. The layers are completely defined by shear modulus, critical-damping ratio, density, and thickness.

3. The soil values are independent of frequency.

4. Only vertically propagating, horizontal shear waves are considered.

The soil model is similar to that developed by Seed and Idriss (1970), using data similar to Hardin and Drnevich (1970). The absolute range of soil parameter variation may be stipulated by merely inputting factors whose numerical values may be derived from simple soil strength properties. These strength properties may be the undrained shear strength of a clay or the relative density for sands. The program requires the definition of the soil profile down to bedrock (defined as seismic velocity 2,500 ft/sec) as well as an earthquake time history record in digital form. The motion used as a basis for the analysis can be given in any layer in the system, and new motions can be computed in any other layer. Maximum stresses and strains, as well as time histories, may be obtained in the middle of each layer. Response spectra may be obtained and amplification spectra determined.

Figure 5 gives a flow chart of two approaches for determining an average surface response spectrum. The approach of using surface-recorded scaled, response spectra matched to the site conditions is thought to be a better representation of actual conditions than the alternative of attempting to compute ground motion propagation from bedrock to the surface. The limitations in the accuracy of the attenuation equation show no statistical difference between peak accelerations recorded on rock and those on soil at comparable distances. Thus, the problem of what level of motion to input must be based on uncertain data. Motion must be artificially brought to bedrock by deconvolution. Unfortunately, motions are usually recorded on the surface and not at bedrock depth. Without at-depth experimental records, one-dimensional wave propagation calculations, although very useful, may have error. Spectral shapes from such calculations cannot be used with absolute certainty. The extent of site amplification is a significant parameter. However, it cannot be computed from wave propagation analysis in absolute certainty. It should be looked at as relating relative soil behavior. Uncertainty is introduced by the choice of material properties used to characterize the site. The assumptions made in one-dimensional analysis are perhaps more hidden and, thus, create a greater confidence in the results.

It is important to consider the major assumption made in wave propagation analysis: that vertically propagating shear waves travel through horizontal layers. For sites close to the fault, the inclined nature of the fault and the close horizontal proximity to the energy source must be considered. The energy released, which is composed of surface and body waves, cannot be represented by a simplified one-dimensional model. Thus, it is questionable whether any attenuation of motion would actually occur. The one-dimensional model is best suited for sites at distances from the source where propagation is essentially through the more competent subsurface (bedrock) layers refracting to the surface. This site may indeed show attenuation to motion originating from distant sources. However, little is known about close-in behavior; there is not enough known to justify a reduction in ground motion without loss of confidence in the results.

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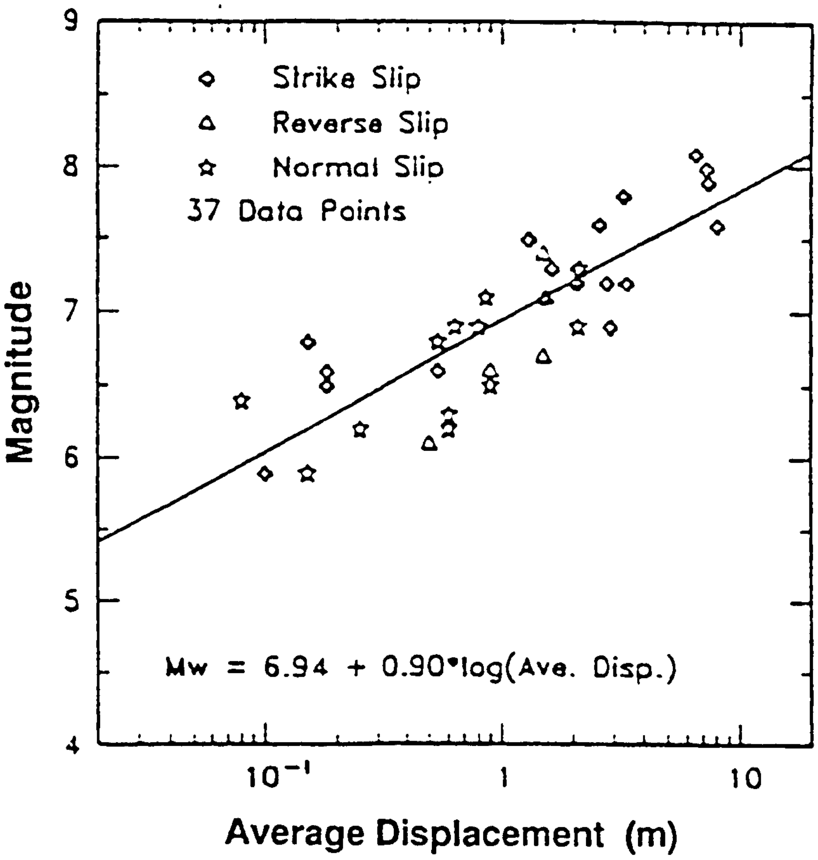

Figure 1. Earthquake Magnitude versus average surface displacement (from Coppersmith, Proceedings Fourth International Conference on Seismic Zonation, 1991)

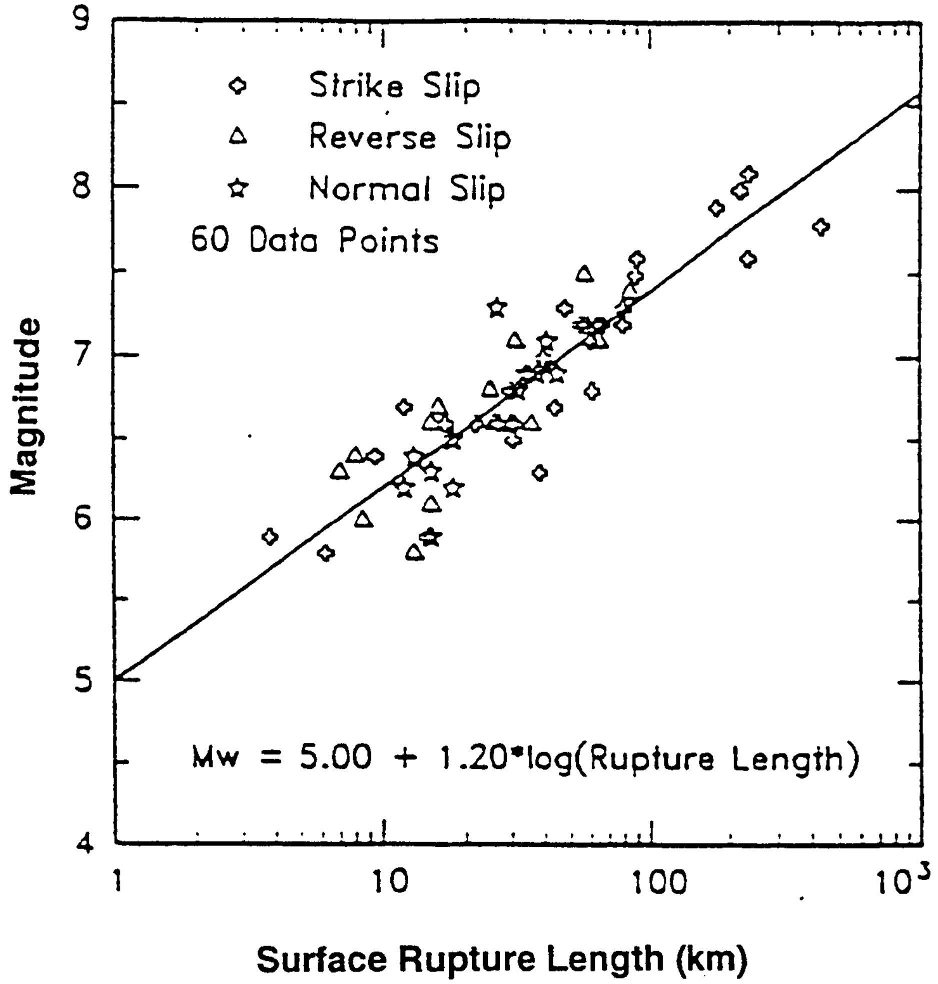

Figure 2. Earthquake magnitude versus fault surface rupture length. (from Coppersmith, Proceedings Fourth International Conference on Seismic Zonation, 1991)

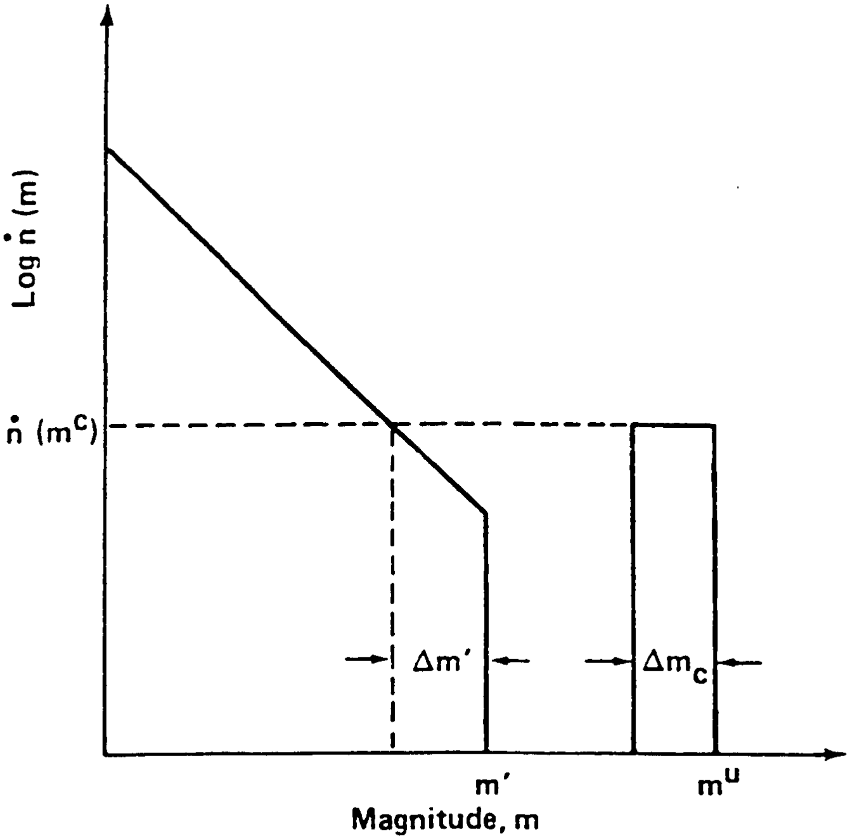

Figure 3. Generalized frequency magnitude density function.

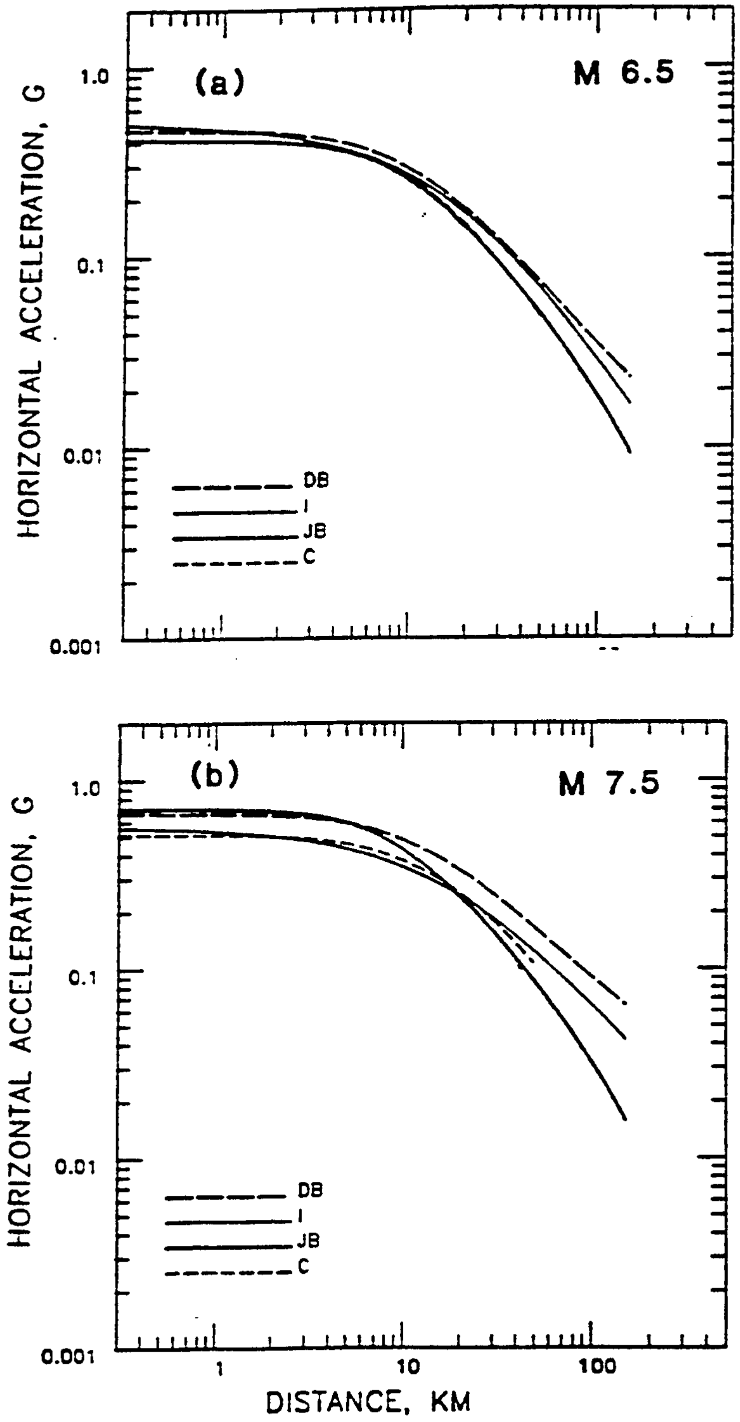

**Figure 4. Comparison of different relationship for peak horizontal acceleration at Magnitude 6.5 and 7.5
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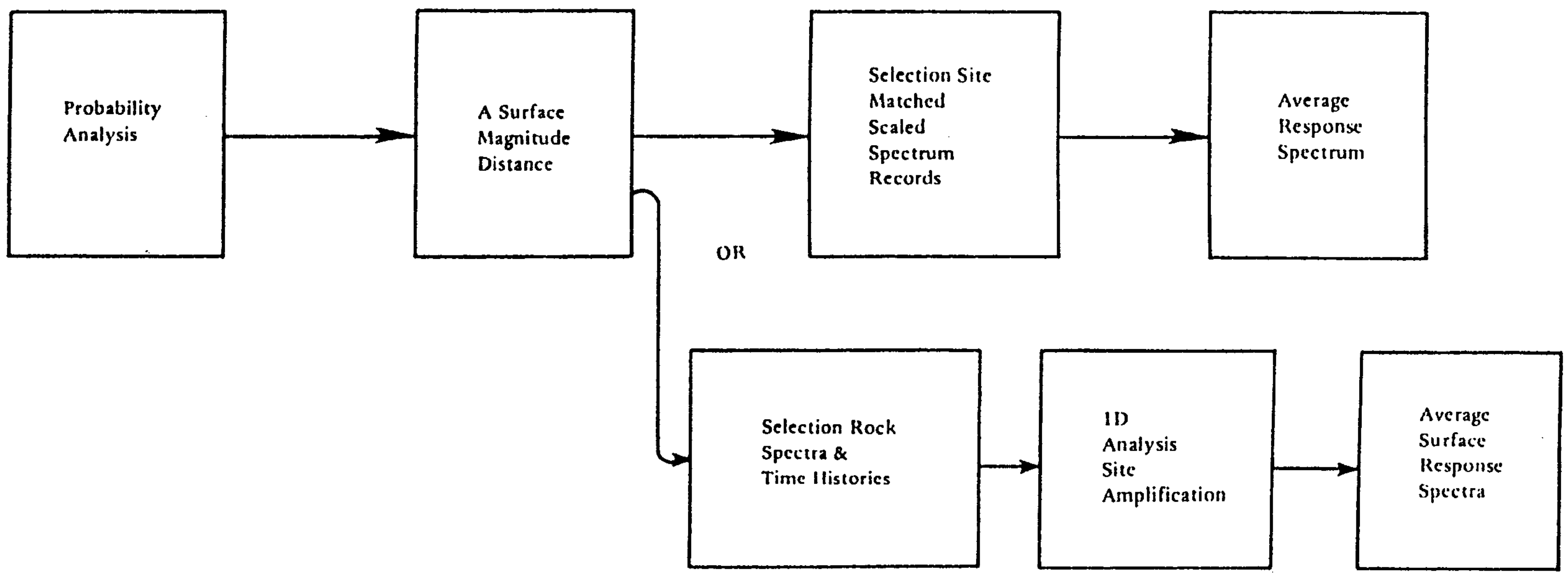

Figure 5. Flow chart of analysis