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Seismic Hazard Analysis

A Methodology for the Eastern United States

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ABSTRACT

This report presents a probabilistic approach for estimating the seismic hazard in the Central and Eastern United States. The probabilistic model (Uniform Hazard Methodology) systematically incorporates the subjective opinion of several experts in the evaluation of seismic hazard. Subjective input, assumptions and associated hazard are kept separate for each expert so as to allow review and preserve diversity of opinion.

The report is organized into five sections: Introduction, Methodology Comparison, Subjective Input, Uniform Hazard Methodology (UHM), and Uniform Hazard Spectrum. Section 2, Methodology Comparison, briefly describes the present approach and compares it with other available procedures. The remainder of the report focuses on the UHM. Specifically, Section 3 describes the elicitation of subjective input; Section 4 gives details of various mathematical models (earthquake source geometry, magnitude distribution, attenuation relationship) and how these models are combined to calculate seismic hazard. The last section, Uniform Hazard Spectrum, highlights the main features of typical results.

Specific results and sensitivity analyses are not presented in this report.

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1.0 INTRODUCTION

In assessing earthquake risk for a given facility, three elements must be considered: the probability that earthquakes of various intensities will occur at the site during future intervals of time (the seismic hazard at the site), the uncertain seismic resistance of the facility, and the uncertain "consequences of damage" which might be sustained by the facility. By combining probabilistic information on seismicity, resistance and consequences, one can assess the probability of various magnitudes of economic and human loss (often called the seismic risk associated with the facility). In this report, we describe approaches for estimating the first factor, seismic hazard, at sites in the Eastern United States.

While all three factors (earthquake hazard, resistance capability, and consequences) are uncertain, it is frequently assumed that, based upon conservative resistance estimates and selection of an "extreme earthquake hazard," the consequences of damage need not be included in the analysis since the probability of damage is very low. In recent years, considerable progress has been made toward deterministically modeling the earthquake mechanisms and the propagation of seismic waves from the source to the site. However, knowledge of these physical phenomena does not yet allow exact prediction of occurrence times and ground motion details. This is especially true for the Eastern United States.

As an alternative to deterministic prediction, seismic hazard can be characterized by direct statistical or indirect probabilistic methods. The direct statistical method uses only historical information at the site and treats this information as a statistical sample. By contrast, the indirect probabilistic approach uses regional and site information to model the sequence of earthquakes from each source as a random sequence and to fit probabilistic attenuation laws. In the latter case, seismic hazard results from a sequence of probability calculations.

Whichever the method, one faces difficulties when dealing with seismicity in the Eastern United States, due to the paucity of data at specific sites (for the statistical approach) or from specific sources (for the probabilistic approach). In addition, source configurations and earthquake mechanisms are not well known. Because of this lack of information, and irrespective of the seismic hazard methodology, one must complement historical data with judgment. The procedures suggested and implemented in this study rely heavily upon the subjective input from selected experts.

The main contribution of this study is a probabilistic model, which systematically incorporates subjective judgment into the evaluation of seismic hazard. We refer to this overall approach, in the following sections, as the Uniform Hazard Model (UHM). Subjective input, assumptions and associated seismic hazard assessment are kept separate for each expert, so as to allow peer review and preserve diversity of opinion.

Some limitations of the model should be noted. From the point of view of methodology, the main limitation is the lack of a clear distinction between systematic errors (uncertain terms which are the same either for different earthquakes or for different spectral ordinates associated with a given earthquake) and random (independent) errors. For purposes of the UHM, errors are typically treated as random. This assumption greatly simplifies the analysis for most areas, and is not likely to cause inaccuracy in the calculated seismic hazard — except in the treatment of attenuation and multiple-degree-of-freedom systems, where classification of errors as systematic or random has more important effects.

For multiple-degree-of-freedom systems the joint probability distribution of several peak spectral ordinates can be important; hence, the output of the UHM as described here provides a conservative evaluation of seismic risk for systems with several contributing modes. For treatment of the attenuation issue, even more caution is warranted. The problem here is the lack of sufficient data from Eastern United States to clearly define both the mean ground motion attenuation and its dispersion around the mean. On the surface, treating both components of this uncertainty as random error appears conservative and is, in fact, a solution of convenience. However, science and mathematics argue against treating both systematic and random error as one aggregate random error since important physical insights are lost and nature's hazard may be incorrectly stated. For lack of sufficient resources this issue has not been adequately treated. On the one hand, a larger value of random uncertainty in attenuation law (including both random and systematic error) has the effect of allowing more distant sources of seismicity to effectively control the hazard and may introduce a bias in the results. On the other hand, smaller values of uncertainty, typical of Western and European data, which are likely more appropriate characterizations of the ground motion variance may result in under- or overestimating the hazard if they are applied without more elaborate analysis of potential systematic errors in the mean attenuation relationship. Because of these limitations, the reader is advised to exercise caution in the application of this methodology.

In the future, we expect to investigate the effect of dependence among uncertain quantities (e.g., for different earthquakes – the configuration of seismic sources, the magnitude-recurrence relationship, form and parameters of the attenuation law, local amplification factors; for a given earthquake – parameters of the attenuation function and attenuation errors at different frequencies).

From the point of view of the numerical results, one should be cautioned against using seismic hazard values for rare events (e.g., events with return period in excess of 5,000 years). These values primarily depend on assumptions about the type of distributions (e.g., of magnitude and attenuation error on which confidence is small).

The report is organized into five sections: Introduction, Methodology Comparisons, Subjective Input, Uniform Hazard Methodology, and Uniform Hazard Spectrum. Section 2, Methodology Comparisons, briefly describes the present approach and compares it with other available procedures. The remainder of the report focuses on the UHM. Specifically, Section 3 describes the elicitation of subjective input; Section 4 gives details both of various mathematical models (earthquake source geometry, magnitude distribution, attenuation relationship), and of methods for combining these models to calculate seismic hazard. The last section, Uniform Hazard Spectrum, highlights the main features of the results.

2.0 METHODOLOGY DEVELOPMENT COMPARISONS

Analytical methods to predict a seismic hazard in the United States have evolved significantly in the last several years. The fundamental problem of all methods is calculating hazards for extreme events at sites where little or no earthquake data exist, and where the physical process of earthquake generation is not well known. In this context, no single proposed methodology has been completely successful because (1) deterministic models must rely on subjective judgment in the selection of parameters for the generation and attenuation of earthquake motions, and (2) even when sample size is adequate for statistical parameters estimation, judgment must be exercised to resolve uncertainty on the form of the models.

Regardless of such limitations, estimates of seismic hazard are often required. Therefore, new methodologies must be developed which, while unable to yield exact answers, combine available objective and subjective knowledge to produce results useful for comparative evaluations. Before describing the approach used here, it is instructive to review the methods proposed in the past.

2.1 DETERMINISTIC APPROACH

Only recently have deterministic approaches been used in the analysis of seismic hazard. These methods directly model the physical earthquake mechanism and the propagation of seismic waves.

Attempts have been made to use deterministic, first principle models for earthquake prediction in the Western United States (WUS). However, even in the West, where seismically active structures can be identified, subjective input and empirical adjustments are required for the models to produce realistic ground motions. Application of the same procedure to sites in the East is not possible at the present time because earthquake mechanisms are not sufficiently known.

To clarify the use of terms, the type of approach outlined in Appendix A of 10 CFR 100 is not considered "deterministic"; in fact, it is not based on first principles. Modeling the physical process is not done; the design acceleration is arrived at by judgmentally choosing the largest credible magnitude and a suitable correlation for ground motion. A major difficulty with this approach is that the seismic protection provided remains unquantified and possibly varies from site to site. Even if one wishes to explicitly account for risk contributors, such as facility age, inventory of hazardous material or structural resistance, it can only be done in this approach by biasing the degree of conservatism in the judgment process.

2.2 STATISTICAL AND PROBABILISTIC APPROACHES

In contrast to deterministic methods, probabilistic approaches (even those with subjective input) can yield results that quantify the degree of safety. However, like deterministic modeling, probabilistic modeling in the Eastern United States (EUS) requires subjective input.

Direct-statistical methods have been applied to West Coast sites wherever substantial data exist. Typically, the parameter that is treated statistically is peak ground acceleration (PGA). If records are available at the site, the entire response spectrum can be analyzed by means of statistical techniques.

An attractive feature of the statistical approach is that it avoids theoretical assumptions required by deterministic and probabilistic models. However, at all eastern sites data are insufficient to make meaningful estimates of medium-to-small probability events. Also, the method usually fails to incorporate physical knowledge specific to the site (e.g., about the location of faults and other earthquake sources) and statistical data at nearby sites. These factors must be introduced by judgment.

The remaining sections of this report describe a probabilistic methodology to calculate values of ground motion parameters (PGA, PGV, and spectral accelerations) with the given chance of being exceeded, at sites in the Eastern United States. The model supplements historical data with subjective input from selected experts. While still suffering from some of the limitations described previously, the method produces rational estimates of seismic hazard, which are especially useful for comparative evaluation of seismic hazard at different sites. The comparative capability allows one to evaluate the consistency of response spectra generated by the techniques, including Appendix A to 10 CFR 100, with Regulatory Guide 1.60 spectra or Housner spectra, selected time histories applied to a specific site, and Newmark-Hall spectra.

2.3 SIMILARITY OF SEISMIC HAZARD MODELS

The fact that, when applied to Eastern United States sites, all available models are limited by paucity of data and by uncertainty on the physical system, generates some similarity among different approaches. First, commonly used models all employ subjective input, usually in the form of opinion from one or several experts to produce reasonable design response spectra. Second, the methods often have substantial overlap since judgmental assumptions are essentially the same, irrespective of the model.

For the purpose of this study, four methods for the definition of design response spectra have been considered in detail. Only one, the Uniform Hazard Method (UHM), is new, in the way it uses subjective input. The others (Newmark-Hall spectra, Real and Scaled spectra) have been available for some time and for this reason, they are not discussed in detail in this report. The response spectra they produce can be "anchored" at points determined by the UHM, or by other procedures.

Newmark and Hall addressed the major problem in the definition of an appropriate spectral shape (i.e., lack of earthquake records in the appropriate categories) and gave the problem a solution based on first principles. At the low and high frequency ends, they forced the spectrum to comply with given peak ground displacement and acceleration values. At intermediate frequencies they suggested that the motion of the ground be amplified, depending on the dynamic characteristics of the system. The high frequency part of the spectrum is scaled with respect to peak ground acceleration, and the intermediate frequency range is scaled with respect to peak ground velocity. In this study, both peak ground acceleration and peak ground velocity are determined on the basis of a given exceedance probability at the site of interest.

Virtually every approach explicitly or implicitly uses a set of real strong motion records in the development of the design spectrum, whether site-specific or generic. For example, the generic NRC Regulatory Guide Spectrum was developed by statistically averaging a set of spectra from historical earthquakes covering a variety of site geologies, magnitudes and distances. Probabilistic models use these records implicitly, for example, in the development of attenuation relations. The approach by real or scaled time histories involves explicit averaging of the records. Of course, the key element of this approach is the selection of records, with a clear tradeoff: the more site-specific the records, the smaller the set of historical earthquakes and therefore the larger the statistical variability of the design spectrum.

If the hazard arises primarily from relatively close earthquakes of intermediate intensity (see Appendix A to 10 CFR Part 100), the selection criteria must explicitly account for this fact. In addition, the criteria must account for regional tectonics (e.g., in the selection of focal depth) and for characteristics of the site that could influence the hazard, most notably, the local geology. While this approach is <u>direct</u> in that it does not involve many of the sophisticated hypotheses required by probabilistic approaches (e.g., earthquakes form a Poisson process), it contains important data-related assumptions. For example, biases are present in any set of digitized strong motion records due to the high priority given by the USGS and others to earthquakes with larger acceleration. Ample room for bias exists in scaling earthquakes of different magnitude.

In general, strong historical ground motions can be used to develop two types of spectra. One possibility is to normalize the records, e.g., to have unit peak acceleration and treat the spectral ordinates of the normalized motions as random variables. This random spectrum can then be anchored at a peak acceleration value determined separately, e.g., from the present hazard analysis.

Alternatively, statistical analysis of spectral ordinates can be performed on the unnormalized records, resulting directly in a site-specific spectrum. An appropriate magnitude range for the records could be selected on the basis of a seismic hazard at the site. Both approaches can use results from the Uniform Hazard Model developed in this report.

2.4 KEY DIFFERENCES BETWEEN THE UHM AND OTHER SEISMIC HAZARD PROCEDURES

There are three major differences between the UHM and empirical and deterministic approaches to estimating seismic hazard in the East. One is that UHM explicitly uses subjective input from experts. As discussed above, all approaches inevitably rely on such input due to the lack of factual information, historical data, and proven first principle models. However, the UHM is explicit in the way it uses such input, it also allows for peer review and assures that expert-to-expert variability of the results is retained. A second difference with some of the other approaches is the inclusion of all, small and large, earthquakes in the final hazard assessment. The third difference involves the format of UHM results: the Uniform Hazard Spectrum does not represent one event or one restricted class of events (e.g., those with small epicentral distance). Since each spectral ordinate combines exceedance probabilities due to earthquakes from all sources, near to and far from the site, it may be unduly conservative to use the Uniform Hazard Spectrum to design multi-degree-of-freedom systems. This issue will be discussed further in Section 5.

Because of these considerations it is believed that the UHM is best used in comparative evaluation of other approaches. For example, in the past many designs have been based on logic similar to that presented in the regulatory approach of Appendix A to 10 CFR 100, often anchoring a Housner spectral shape to a peak ground acceleration value. This spectral shape was derived from several large western motions and that in application it was scaled to an appropriate eastern peak acceleration. A similar approach is used now, except that the shape is determined by Regulatory Guide 1.60. The latter spectral shape is roughly the mean plus one sigma of a large number of, again, scaled western records. The appropriateness of either of these approaches can be evaluated by comparing the four methodologies previously discussed.

2.5 FUTURE DEVELOPMENTS BEYOND THE UHM

Additional probabilistic methodology developments are expected in the near future as a result of NRC's Seismic Safety Margin Research Program. As part of this program, Monte Carlo integration techniques are proposed to calculate the seismic risk of a given facility at a typical eastern site. Additional development of subjective input is also planned. One strength of this proposed approach over the UHM in this study is the ability to identify the contribution of individual earthquakes to the final seismic risk. This feature will allow additional sensitivity analysis to model assumptions and will undertake ways to improve the design.

Another promising approach to seismic hazard analysis in the east would be to combine recently developed first principle deterministic models with empirical statistical analysis of western and European earthquakes. Substantial data are available for such statistical analysis, although most records have not yet been digitized to allow convenient analysis. In this way, it may be possible to weaken dependence of the results on subjective input.

3.0 SUBJECTIVE INPUT FROM EXPERT OPINION

Previous sections of this report have emphasized that seismic hazard assessment for Eastern United States sites always requires some degree of subjective input, either in modeling assumptions, or in providing input data, or in both operations. It is our opinion that this need should be acknowledged and that subjective input should be formally solicited using as much expert opinion technology as possible.

As described in Section 4.0, the Uniform Hazard Methodology for the assessment of seismic hazard at Eastern United States sites attempts to do this through the use of a questionnaire and an expert panel. The results of this solicitation are summarized in a separate companion report, "Seismic Hazard Analysis: Solicitation of Expert Opinion."

The purpose of this section is to summarize the approach used to generate subjective input. Methods of expert opinion solicitation, biases and modes of judgement are discussed in Appendix B. Appendix B also contains a description of the questionnaire used in this study and discusses the role of the expert panel.

3.1 EXPERT OPINION AND EASTERN U. S. SEISMICITY

Analysis of seismic hazard in the Eastern United States presents several challenging problems that a probabilistic approach can answer, with the help of expert opinion and subjectively assessed probabilities. The main issues are:

a. The central and eastern regions of the United States are notable for their low level of seismic activity, which is rather uniformly distributed over rather large areas (e.g., the Central Stable Region). A few restricted areas have experienced major earthquakes, together with continuous activity, above this moderate background seismicity. Since the correlation between epicentral location and geological and geomorphologic features is generally very controversial, the determination of seismic source boundaries can best be made either subjectively or statistically, by noticing anomalies in the mean occurrence rate or in the intensity distribution. In either case, experts' opinion on seismic source location appears to be critical for the development of a tectonic model in the East.

b. The low activity of the regions that are occasionally disturbed by major events does not provide a good basis for applying classical statistics. At the level of seismic hazards usually desired, classical statistics gives results that are affected by too much uncertainty. Additional uncertainty results from the difficulty of addressing such points as: (1) To what extent should large events be treated as anomalies? (2) What is the probability that such events may occur elsewhere? Because insufficient geological and seismological data are available, only experts' opinions can be used to shed light on these questions. In our model, subjective probability is used in connection with three parameters: rate of occurrence, distribution of magnitudes, and upper magnitude cutoffs.

c. The lack of instrumental records in the East forces the analyst to work with intensity data. Unfortunately, at the epicenter, the data show a large scatter when correlated with magnitude; and at the site, intensity measures contain much less information than a motion record. Due to these limitations, the development of attenuation relationships can greatly benefit from the opinion of qualified experts.

In conclusion, we believe that seismic hazard analyses in the East cannot be based on historic data alone and that, at a minimum, data should be complemented with expert judgment.

3.2 QUESTIONNAIRE ON EASTERN UNITED STATES SEISMICITY

A questionnaire was developed to elicit expert opinion on seismicity and intensity attenuation in the Eastern United States. Since available historical data were submitted to experts, it was considered unreasonable that they would divorce themselves from this information while answering the questionnaire. This means that although Bayesian analysis was not used to formally combine information from data with additional information and beliefs held by each expert, the answers could be considered as <u>posterior</u> estimates. In fact, experts were explicitly instructed to temper the data from Eastern United States sites their general experience in each seismic region, by likely similarities with other seismic provinces, by geologic and tectonic considerations, and by other relevant factors. Effectively, we asked experts to act as Bayesian processors of information.

The Eastern United States data made available to the experts were based on a comprehensive catalog of earthquake events assembled from various regional catalogs for the east. For each zone, experts were supplied with: (1) a list of all earthquakes having epicentral intensity of IV or greater, and (2) a table giving the number of earthquakes of each Modified Mercalli (MM) intensity unit from IV through XII.

The questionnaire was divided into five sections:

- Source Zone Configuration
- Maximum Earthquakes
- Earthquake Occurrence
- Attenuation
- Self Ranking

Redundancy was designed into the questionnaire to allow for cross-checking answers and to establish consistency. Even so, followup was necessary in certain areas to obtain usable results.

Responses to each question could be given in one of several ways, all of which could be converted to a usable format for analysis. These ways were:

- A best estimate only, interpreted as a known value
- A range of values defined by a lower and an upper bound, interpreted to mean a uniform distribution within the range
- A range of values defined by a lower and an upper bound with nonuniform distribution
- A written discussion

In addition, for the section on Source Zone Configuration, each expert was given maps showing two possible seismic zonations to be rated and modified if required.

4.0 UNIFORM HAZARD METHODOLOGY

A uniform hazard spectrum is defined as "a spectrum, the ordinates of which have the same probability of being exceeded in a given number of years". All events capable of affecting the site are considered in assessing the probability of exceedance.

4.1 PHILOSOPHY OF APPROACH

Seismic hazard is usually quantified through the probability distribution of the peak value of ground motion parameters at the site, during a given interval of time. This distribution can be calculated for any parameter for which it is possible to define an appropriate service model, transmission model and site effect model. A typical seismic hazard evaluation proceeds through four steps:

- Seismic source identification
- Definition of an Earthquake Occurrence Model for each source
- Formulation of an attenuation model
- Evaluation of seismic hazard at the site

Several methods are available by which seismic hazard can be estimated (e.g., Cornell and Merz, 1974; Der Kiureghian and Ang, 1975; McGuire, 1976; Algermissen and Perkins, 1976; Shah and others, 1975; and Mortgat and others, 1977). Although all of these procedures utilize the four steps noted above, differences exist -- in key assumptions and modeling details -- which can produce significantly different results.

The seismic hazard procedure used in the present study shares the same basic steps.

Seismic Source Geometry

- Define representations (zones) for source geometry

Earthquake Occurrence Model

For each source in the Eastern United States:

- Define location and magnitude range
- Define earthquake recurrence:
  - (a) mean rate of occurrence
  - (b) magnitude distribution

Attenuation Model

- Define applicable mean attenuation relationships
- Define uncertainty about mean values

Exposure Evaluation Model

- Define procedure for computation of probability of exceedance

Treatment of Error

Uncertainties of two different types, systematic and random, contribute to seismic hazard. Systematic uncertainty is that associated with errors in the form and parameters of models used in the course of the analysis (e.g., form and parameters of the attenuation law, upper bound magnitudes, site amplification factors). We call it systematic because it uniformly affects all earthquake events (or at least more than one event), as they are felt at the site. By contrast, the random component of uncertainty represents independent variation from earthquake to earthquake (e.g., the magnitudes of different earthquakes, given their common distribution, or the random uncertainty associated with attenuation models). Uncertainties are classified as systematic or random because these components require separate treatment. A detailed treatment of systematic and random errors is presented in Appendix A.

Given the large number of conditional analyses required for appropriate treatment of systematic uncertainty on many parameters, a simplified procedure may be adopted in which the effect of systematic uncertainty is evaluated separately for each parameter (or for a small set of parameters), and only the components found to be important will be retained in the final analysis. In the approximation, the less important parameters may be treated either as known constants, or as random variables which are independent from event to event (thus modeling uncertainty as random rather than systematic).

In this study, systematic uncertainty is treated in a number of different ways, depending on the parameter. Specifically,

- The input from each expert was kept separate and processed on an individual basis. This method of independent analysis accounts for systematic bias in expert opinion. A consensus was reached at the results stage.
- Uncertainty on seismic source geometry was treated by considering two bounding hypotheses. No combination of the associated results was attempted.
- Systematic uncertainty on attenuation was also treated through sensitivity analysis by considering different alternatives. Again, no integration of the results was attempted.
- Other uncertainties, such as those on the mean occurrence rate and on the magnitude distribution (including upper magnitude cutoff), have been treated as random.

4.2 SEISMIC SOURCE GEOMETRY

Typically, the location of a seismic source is determined both from the hypocentral position of past earthquakes, and from geological and seismological information. Three types of source are commonly used to represent the seismicity of a region. They are the point, line or area source at constant depth in the earth's crust. The location of future seismic activity within a particular region is thus restricted to the sources, and seismicity is assumed to be homogeneous (uniform) inside each source.

Since the shape and location of a source has some influence on the final results, special care was taken in this study to obtain the best possible estimates of these characteristics.

In the Eastern United States, seismicity is distributed almost uniformly over large regions, and therefore, most sources are of the area type. Their boundaries have been approximated by a series of straight lines (Figure 4-1). Since activity is usually restricted to a narrow depth range, the sources were assumed to lie on horizontal planes with constant depth.

Line sources have been used to model seismicity in regions where historical hypocenters are either constrained to a narrow band along a line at constant depth, or clustered around a known fault. Each such source has been broken up into several straight segments, as shown in Figure 4-2. Since few active faults have been precisely located in the East, this model was only rarely used. In no case was it found to be necessary to use single-point sources.

We have not used the "significant distance" concept that is employed in the fault-rupture model for seismic hazard analysis first proposed by Ang (1974) and further developed by Der Kiureghian and Ang (1975, 1977). Even though our computer code can accommodate the notion of significant distance, epicentral distance, instead, was used in the analysis since the attenuation relationship was developed from epicentral distance data.

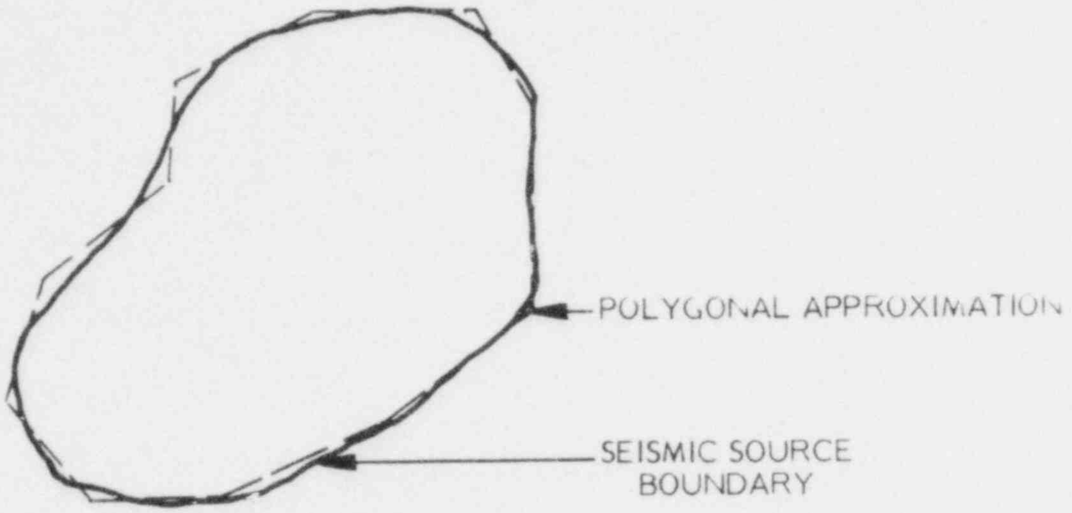


FIGURE 4-1

TYPICAL AREA SOURCE

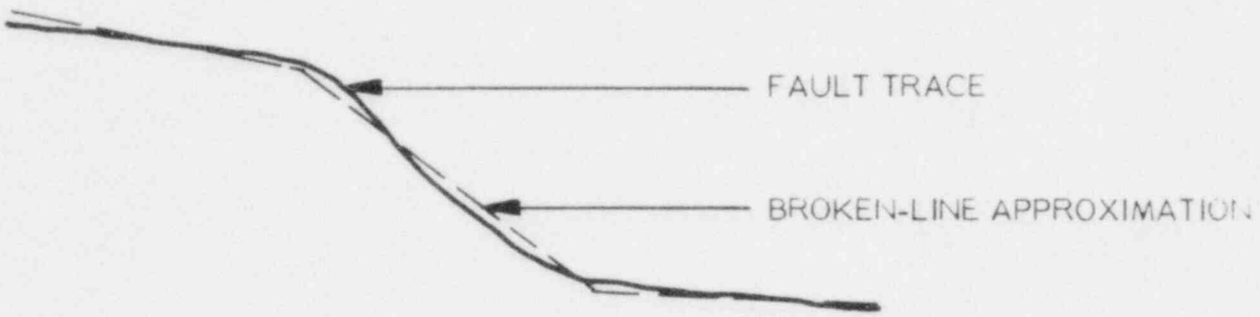


FIGURE 4-2

TYPICAL LINE SOURCE

Expert Opinion

In the following discussion, source refers to a source of seismic activity, whereas zone, zonation or configuration refers to the boundary that defines the source geometry. Hence, a source like New Madrid can be modeled by a number of zone alternatives.

As described further in Appendix B, maps with two possible seismic zonations of the Eastern United States were provided to the experts. Each expert was then asked to modify or add any source he considered necessary and to associate a likelihood ("credibility") with each zone alternative. This operation produced a number of source configuration alternatives (zones), each with its own likelihood.

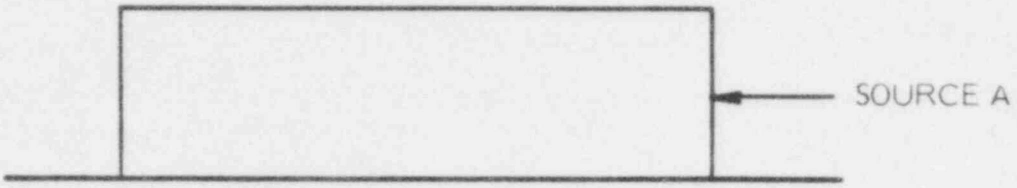
A number of interpretations can be given to this input information for use in hazard analysis. We chose two interpretations that, for the sites appropriate to this analysis, should produce bounds to the seismic hazard: one, more conservative, allows some earthquake activity over a background region larger than that provided by each single expert; the other, less conservative, removes some of the uncertainty by considering, for each expert, only the configuration alternative suggested by that expert.

Interpretation I

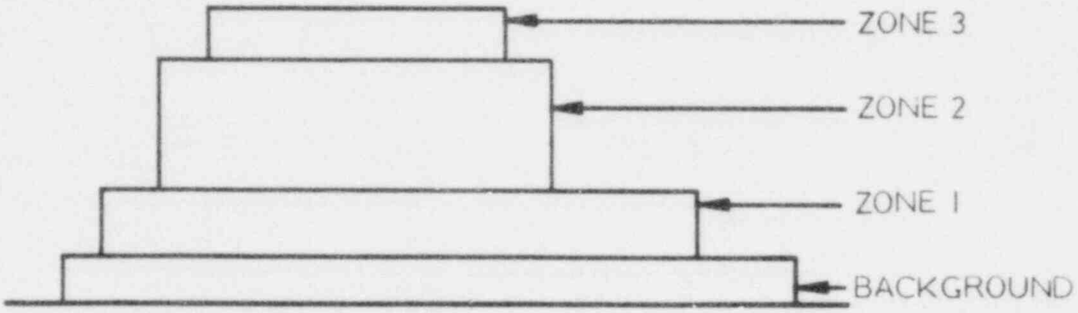
All zone alternatives from one expert were simultaneously considered, and seismicity was distributed among them as a function of "credibilities." This operation resulted in a mean rate function μ that has stepwise discontinuities over each source (Figure 4-3). Specifically, credibilities (likelihoods) were first normalized, and the resulting quantities,

$$P_i = C_i / \sum_j C_j \quad ,$$

were treated as probabilities. (Subscripts of P and C identify configuration alternatives (zones) for the source under consideration.) Then, each source was



CLASSICAL
APPROACH



ZONE SUPERPOSITION
ACCORDING TO INTERPRETATION I

Figure shows a section through the source and assumes that three configuration alternatives (zones) are identified.

FIGURE 4-3

MEAN OCCURRENCE
RATE FUNCTION FOR SOURCE A

modeled as the superposition of all of its alternative configurations, and the mean occurrence rate for configuration i was taken to be

$$\lambda'_i = \lambda P_i$$

where λ = mean occurrence rate for the source.

A final, additional operation was performed on the λ'_i to take into account the fact that some experts heuristically assigned credibilities to reflect their overall confidence in zonation alternatives. For example, the assignment $(C_1,C_2) = (0.9,0.9)$ seems to indicate more confidence than $(C_1,C_2) = (0.1,0.1)$. This operation required an additional source configuration, "background", which was defined to be the union of the zone alternatives considered by all experts. The probability of the background configuration was assessed as

$$1 - P_A = \prod_i (1 - C_i) \ .$$

(Credibilities are assessed on a scale from 0 to 1.) At one extreme, if any one of the C_i is equal to 1, then $1 - P_A = 0$, and the background configuration is excluded. At the other extreme, as $C_i = \rightarrow 0$, for all i, the probability of the background approaches 1. Finally, the mean occurrence rates for the various configurations were estimated as

$$\lambda''_i = P_A \lambda'_i$$

for all zones except the background, and

$$\lambda''_A = \lambda(1 - P_A)$$

for the background. Notice that

$$\lambda''_A + \sum_i \lambda''_i = \lambda$$

Sensitivity of the final results to P_A depends upon the alternative configurations of the source, the site location and the attenuation model. In most of the numerical calculations, sensitivity was found to be small, and the present procedure was found to be conservative with respect to removal of the background (when setting $1 - P_A = 0$).

We recognize that the relation

$$1 - P_A = \prod_i (1 - C_i)$$

has not been developed strictly from probability theory. However, we feel that this heuristic treatment of a difficult technical problem, as necessitated by the format of available information, satisfactorily quantifies the confidence of the experts in their source models. This interpretation will be referred to as "background zonation."

Interpretation 2

The second interpretation does not overlay zone alternatives of the same source; rather, it uses the zonation provided by each expert, recognizing that he had the highest confidence in his own opinion. Therefore, seismic activity was modeled by a set of adjacent zones (selected to have the most likely configuration, and hence, without overlay) with probabilities equal to 1, and no background was used.

This zonation will be referred to as "no background zonation." It is generally a less conservative approach than the previous one because it imposes more restrictions on the location of earthquake epicenters.

4.3 EARTHQUAKE OCCURRENCE MODEL

For each source, the parameters of the earthquake occurrence model, required by the present analyses, are the magnitude distribution (including the upper magnitude cutoff) and the mean rate of occurrence. Although the size of earthquakes is expressed in terms of magnitude, M, this quantity can be replaced by any other measure of intensity at the source (e.g., by epicentral MMI).

Data on earthquake size are discretized every 1/4 of magnitude or ½ MMI, as is commonly done in earthquake catalogs. This representation allows the use of a discrete distribution model and is advantageous in that it avoids the standard log-linear fitting which is unacceptable in some cases; it also allows the use of efficient statistical estimation algorithms.

Estimation is completed in two steps:

(1) Assuming that only ground motions with $M > 4$ are of interest and that occurrence of earthquakes with magnitudes greater than 4.0 follow a Poisson process, the mean occurrence rate, λ, is estimated (e.g., from data) as

$$\lambda = \frac{\text{no. of earthquakes with } M > 4 \text{ in } (t_1, t_2)}{t_2 - t_1} ,$$

or from subjective input.

(2) The discrete magnitude distribution

$$\left\{ p_{M_i} = P\left[M = M_i\right] \right\}$$

is determined either from data or from subjective input. A simple, data-based estimate is

$$\hat{p}_{M_i} = \frac{n_i}{n} ,$$

where n_i is the number of earthquakes with magnitude M_i out of a total of n events.

(A procedure for estimating the same probabilities using expert information is given later in this section.)

Number of Earthquakes in Time and Space (Poisson Model)

Once the seismic sources have been located, it is assumed that earthquakes from each source occur in space and time according to a Poisson process. In order for earthquake events to be considered as forming a Poisson point process, the following conditions must be satisfied:

1. Spatial independence
2. Temporal independence
3. Negligible probability for two or more seismic events taking place at the same time and at the same location.

The first two assumptions imply that the occurrence/absence of a seismic event at one site and time does not affect the occurrence/absence of seismic events at other sites or times (i.e., the process has no spatial or temporal memory). This is a common modeling assumption, and although the mechanism of stress accumulation and release seems to contradict it, the earth's "memory" appears to fade rapidly enough in time (Garner and Knopoff, 1974) to give this assumption effective validity. The third assumption implies that, over a short time interval, more than one seismic event cannot occur inside a small geographical region. For main shocks this is a reasonable assumption, and it also complies with our understanding of the physical phenomenon.

Given the mean occurrence rate λ for all earthquakes from a given source, the probability of exactly n events from the source during a time interval of duration t is

$$P_N(n \mid \lambda) = \frac{e^{-\lambda t} (\lambda t)^n}{n!} \quad , \quad t > 0 \ ; \ n \text{ integer} \geq 0, \tag{4-1}$$

In particular,

$$P_N(0 \mid \lambda) = \frac{e^{-\lambda t} (\lambda t)^0}{0!} = e^{-\lambda t} \tag{4-2}$$

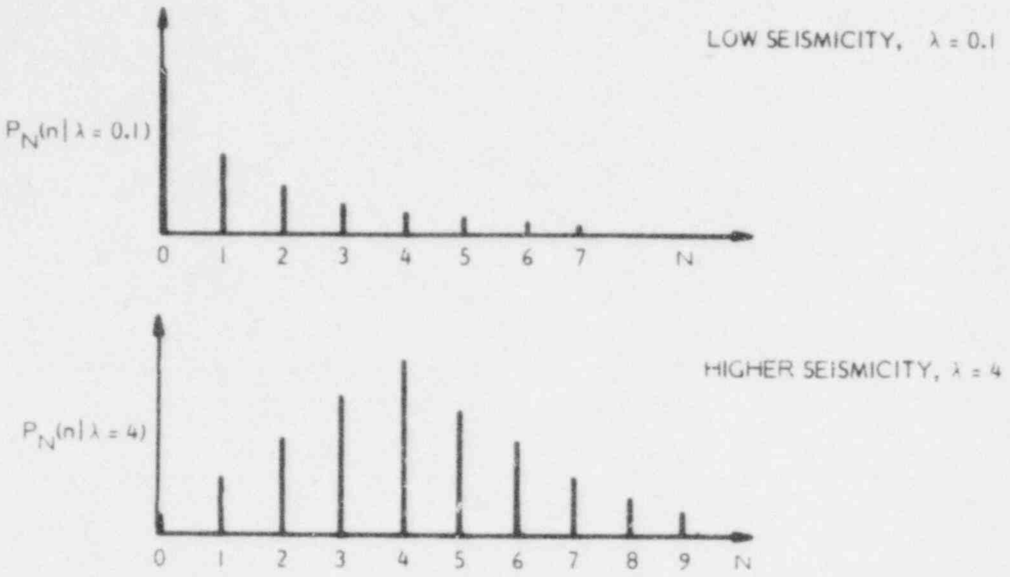
$$P_N(1 \mid \lambda) = e^{-\lambda t} \lambda t$$

Typical plots of the Poisson probability masses in Equation 4-1 are shown in Figure 4-4a.

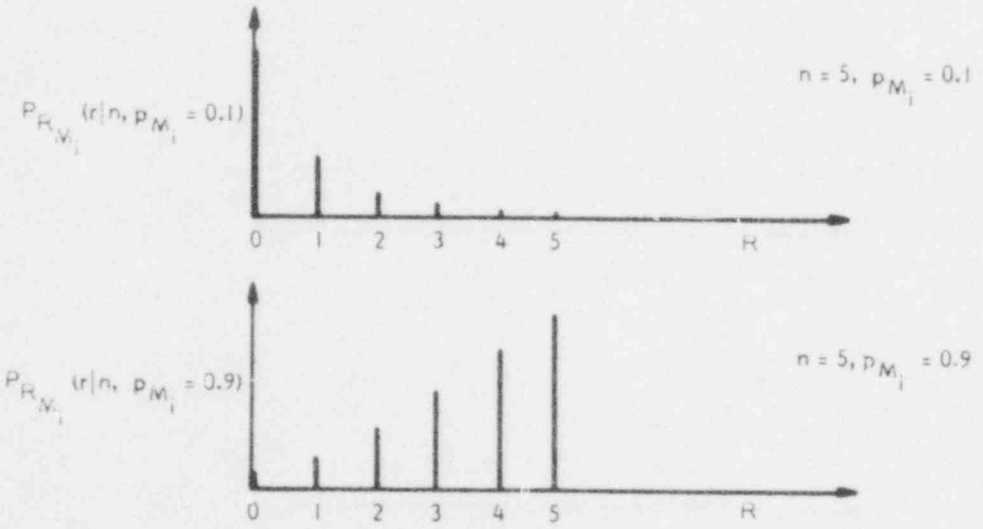
Whenever an expert assigned a value to λ, that value was interpreted as the actual mean occurrence rate. In most cases, λ was not given and had to be estimated from data. Thus, in recognition of the fact that λ cannot be calculated exactly from a finite catalog of events, this parameter was considered to be random, with the gamma distribution that results from Bayesian analysis of the data, with noninformative conjugate prior.

Magnitude Distribution

The cumulative distribution function of magnitude, $F_M(m)$, is uncertain in a way that would be best represented by a correlated random process. The process should satisfy obvious constraints such as $F_M(0) = 0, F_M(\infty) = 1$, $F_M(m)$ nondecreasing. Such a process should be nonparametric (i.e., should express a state of uncertainty that cannot be explained through only a finite number of random parameters). The formulation and analysis of $F_M(m)$ as a random process is difficult and, for this reason, parametric approximations (e.g., truncated expo-



* (a) POISSON DISTRIBUTIONS FOR N



(b) BINOMIAL DISTRIBUTIONS FOR R_{M_i}

FIGURE 4-4 a

TYPICAL POISSON AND BINOMIAL DISTRIBUTIONS nential distributions with uncertain decay and upper bound parameters) are often preferred.

Such parametric approximations are done for convenience and expedience. Alternatively, the possible values of M may be discretized, and simple nonparametric random distribution models may then be used. The simplest model of this type which satisfies the constraints

$$0 \le p_{M_i} \le 1 \text{ and } \sum_i p_{M_i} = 1 \tag{4-3}$$

is the so-called Dirichlet model, with marginal beta distribution for the p_{M_i}.

In this report, a marginal beta distribution for each M_i has been fitted to the parametric model provided by each expert. Numerical results directly using the parametric model are almost identical.

The two extreme models, parametric and nonparametric with independent marginal beta distributions, should bound more realistic (but more complicated) nonparametric dependent models. Insensitivity of the results gives confidence in the results from the present procedure.

In the discrete model,

Let p_{M_i} = probability that $M = M_i$ for the generic event

and $q_{M_i} = 1 - p_{M_i} = P\left[M \neq M_i\right]$

Then, the probability that r out of n events are of magnitude M_i is

$$P_{R_{M_i}}\left(r \middle| n, p_{M_i}\right) = C_n^r p_{M_i}^r \left(1 - p_{M_i}\right)^{n-r} \tag{4-4}$$

with n integer > 0

r integer; $0 \leq r \leq n$

$0 \leq p_{M_i} \leq 1$

and with C_n^r the binomial coefficient

$$C_n^r = \frac{n!}{r!(n-r)!}$$

Typical plots, of $P_{R_{M_i}}(r \mid n, p_{M_i})$ versus r are shown in Figure 4-4b.

The distribution of Equation 4-4 is conditional on given p_{M_i}. In practice, this probability is uncertain and should be treated as a random variable. This was done through the procedure described below.

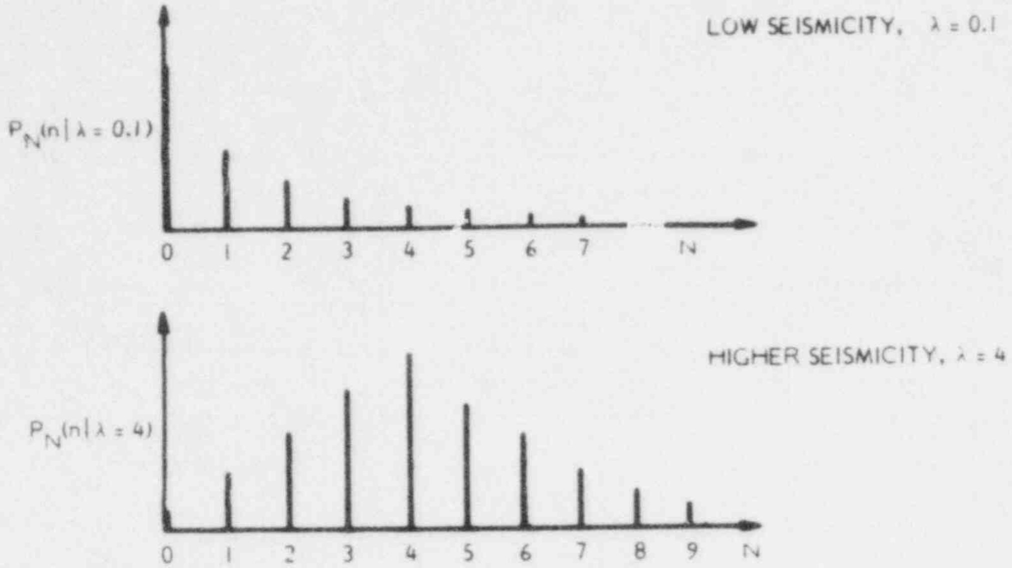
All experts chose to express the magnitude-frequency law in terms of the log-linear relationship

$$\log N_c = a + b M \qquad (4\text{-}6)$$

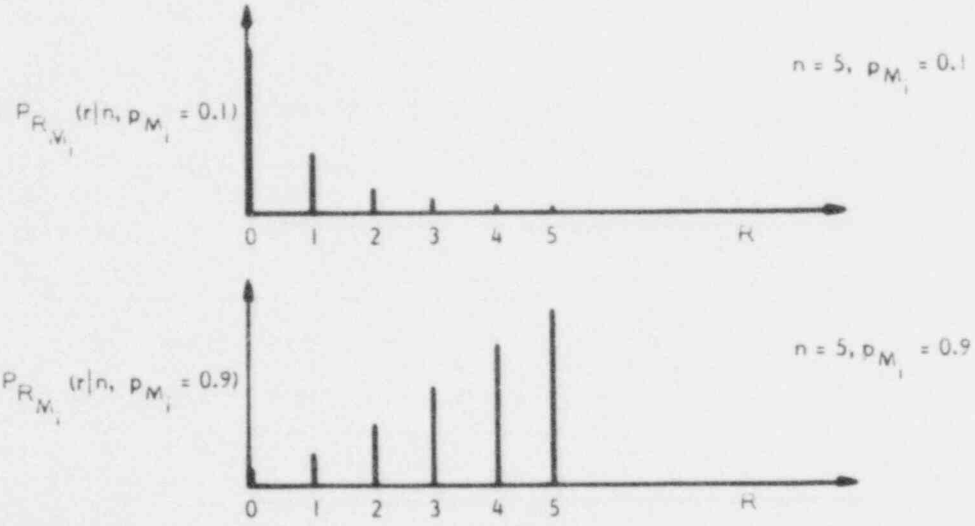
where N_c = number of earthquakes with magnitude $\geq$ M from a given source and over a given interval of time.

The slope b was given by each expert either as a fixed value (e.g., 0.9) or as an estimate associated with uncertainty (e.g., 0.9 ± 0.1).

On many occasions, the parameter a was not provided. In these cases, the a value was determined directly from the data, corrected for nonhomogeneity in time (Appendix C), and from other information provided by the questionnaire (such as the return period of large events). In all cases, the recurrence relationship from expert opinion was superimposed to an empirical estimate using data only, as a check of consistency. A typical plot is shown in Figure 4-5.



(a) POISSON DISTRIBUTIONS FOR N



* (b) BINOMIAL DISTRIBUTIONS FOR R_{M_i}

FIGURE 4-4b

TYPICAL POISSON AND BINOMIAL DISTRIBUTIONS

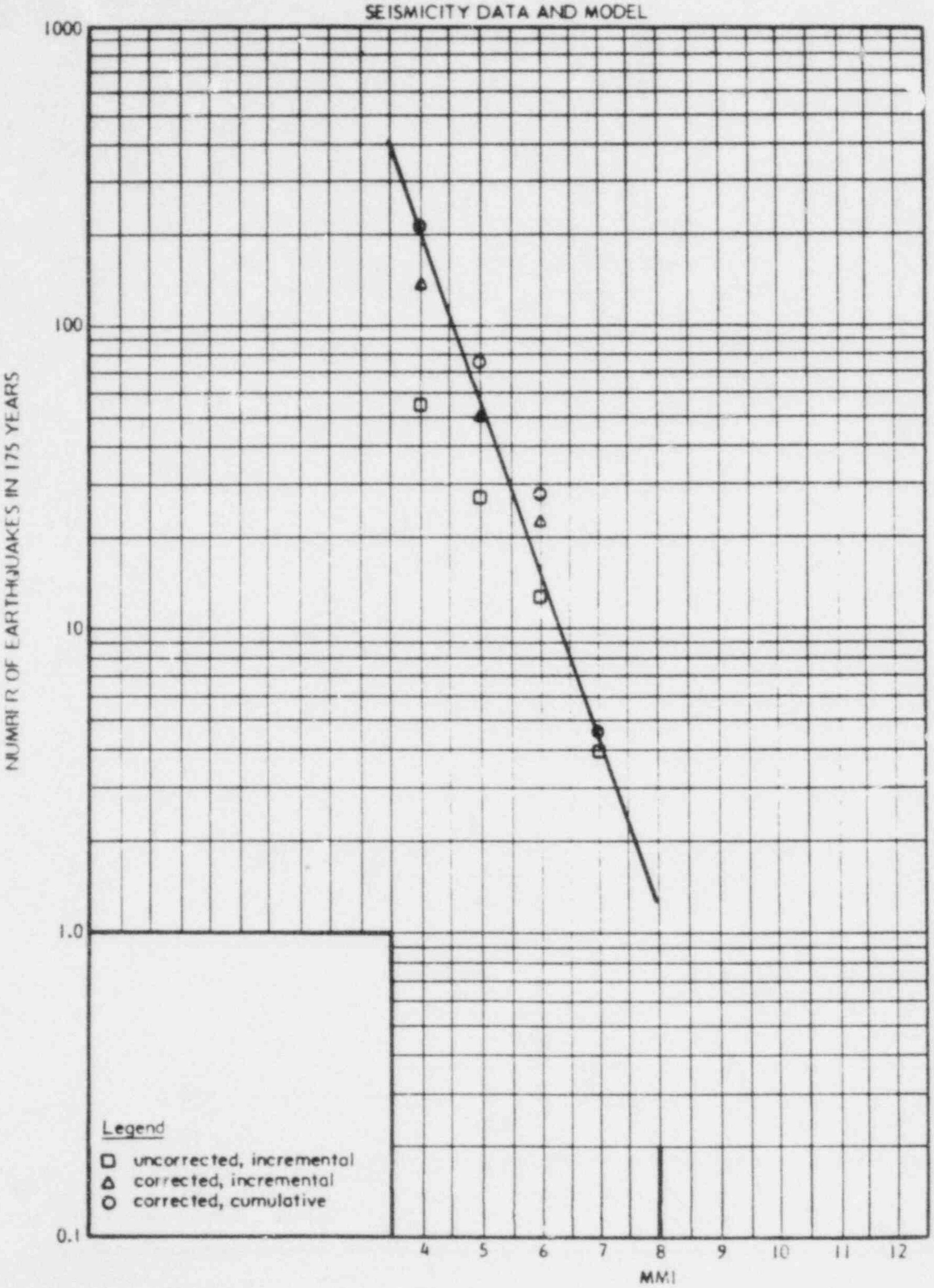


FIGURE 4-5

TYPICAL PLOT OF DATA, CORRECTED DATA AND FITTED RECURRENCE RELATIONSHIP

Uncertainty on the recurrence slope was modeled by using an appropriate beta distribution for the p_{M_i}.

Let $$p_{M_i} \sim \mathrm{BETA}(\eta_i, \xi_i) \tag{4-7}$$

With

$$E\left[P_{M_i}\right] = \frac{\xi_i}{\eta_i}$$

and

$$\mathrm{Var}\left[P_{M_i}\right] = \frac{\xi_i(\eta_i - \xi_i)}{\eta_i^2(\eta_i + 1)}$$

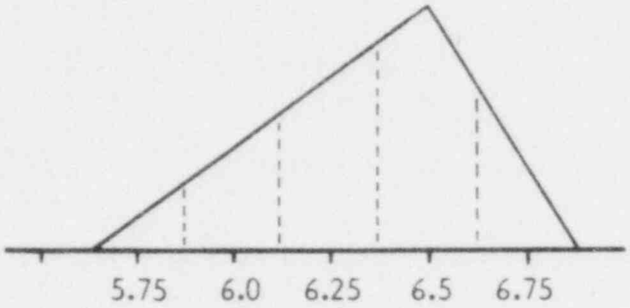
First, ξ_i and η_i were found by the method of moments, for $M_i = 6$, assuming that the exceedance probabilities associated with the extremes of the range of b given by the expert correspond to a 2-sigma dispersion interval. For all other magnitudes, the parameter η_i was kept constant and ξ_i was varied to reproduce the exponential expected value function. Finally, a correction was made to the parameters ξ_i, to account for uncertainty on the upper bound magnitude.

Largest Earthquake (Upper Magnitude Cutoff)

Expert information on the upper magnitude cutoff, M_U, was in the form of either one upper bound magnitude value or a range of magnitudes, plus a best estimate. When the upper magnitude cutoff was given as a single estimate, say M_i, it was assumed that no event greater than M_i could occur, and therefore, p_{M_j} was set equal to zero for all $j > i$. When the upper magnitude cutoff was defined by a range of magnitudes, a triangular distribution was assumed over the range with mode at the best estimate (Figure 4-6). The probabilities, $p_{M_U}(M_i)$, with M_i inside the range, were obtained from that distribution and incorporated in the analysis through modification of the parameters in Equation (4-7).

DATA ON M_u

LOW BOUND	5.75
HIGH BOUND	6.75
BEST ESTIMATE	6.50



m_i	$p_{M_u}(m_i)$
5.75	.057
6.0	.172
6.25	.286
6.5	.352
6.75	.133

FIGURE 4-6

TRIANGULAR DISTRIBUTION OF MAXIMUM EARTHQUAKE

Let the distribution of p_{M_i} from information on b alone be of the beta type with parameters η_i and ξ_i, and suppose that the upper bound magnitude has discrete distribution $p_{M_U}(M_i)$. Then, for each magnitude M_i, the parameter ξ_i was replaced by a new parameter, ξ_i', where

$$\xi_i' \propto \xi_i \sum_{j>i} p_{M_U}(M_j)$$

The proportionality constant is chosen to satisfy

$$\sum_i \frac{\xi_i'}{\eta_i} = 1 \ ,$$

The above correction procedure is not obtained from rigorous mathematical deduction; however, it reasonably applies the information provided by the experts and yields realistic magnitude distribution models.

4.4 ATTENUATION RELATIONSHIPS

Quantifying attenuation in the Eastern United States (EUS) is difficult due to almost complete absence of strong-motion data. Inferences about the attenuation of ground motion in the East must thus be made by studying systematic differences or similarities between the EUS and other regions of the world regarding information that is indirectly related to ground motion (such as intensity data).

Introduction

As a preliminary attempt to focus on the problem of attenuation in the EUS, it is valuable to offer evidence which may shed some light on the differences or similarities between ground motion attenuation in the EUS and the Western United States (WUS), such as:

- MM intensity attenuates more slowly in the EUS than in the WUS, based on an abundance of historic intensity data.
- Propagation velocities are higher at depth in the EUS than in the WUS.
- There are higher Q-values (lower damping) in the EUS than in the WUS.
- There is no low Q-zone in the upper mantle in the EUS.
- There are systematic differences among magnitude determinations between the EUS and WUS.

Some inferences concerning differences in ground motion characteristics between these two regions may be made from the above evidence. They can tentatively be quantified in terms of differences in frequency content, amplitude and duration of the motion.

- The relative damageability of ground motions (in the far field as compared to the near field) is greater in the EUS than in the WUS. This implies a relatively larger energy content and
  - (a) larger accelerations, or
  - (b) longer durations, or
  - (c) both (a) and (b)
- The amplitude of body waves at the larger distances is greater in the EUS than in the WUS.
- The EUS may be a more efficient propagator of surface waves than the WUS. This would imply relatively longer durations and larger long-period motions in the EUS.
- There may be fewer complexities in the transmission path in the EUS. This could explain in part the lower damping inferred in the EUS. It might imply less scattering of waves, making the EUS a relatively more efficient propagator of the higher frequency motions.

- Since there are more competent rocks at depth in the EUS, earthquake foci may be deeper. This might imply lower attenuation of ground motion as compared to the WUS at distances less than several focal depths. This would not explain differences in attenuation at greater distances.

- Source parameters relative to the "size" of an earthquake may be different in the EUS than in the WUS. The higher competency of the rock and lack of major, well-developed fault zones might imply higher stress drops and smaller source dimensions in the EUS.

Approach

It would seem that, aside from theoretically modeling, there are very few technically reasonable alternatives to EUS attenuation, given the paucity of strong motion data and availability of intensity data. Our recommended approach consists of developing a model for the attenuation of site intensity using EUS intensity data, and applying existing EUS strong motion data in conjunction with data from the West to convert the site intensity into a ground motion parameter. The ground motion parameters chosen for this analysis are peak ground acceleration (PGA), peak ground velocity (PGV), and several spectral ordinates at frequencies ranging from 25 Hz to 0.5 Hz. The site intensity is also retained as an additional measure of the ground motion.

As discussed elsewhere, we have calculated the seismic hazard at specific sites, using ten separate sets of input corresponding to the data and opinions provided by ten experts. Many of the experts preferred to deal with seismic hazard in terms of epicentral intensity, and our attenuation relation (as described above) is appropriate for use with these experts' input. Other experts preferred body-wave magnitude, and for these experts we factor out epicentral intensity as a parameter in the attenuation model using a correlation between body-wave magnitude and epicentral intensity.

The strength of this approach is that it specifically models the EUS by explicitly incorporating EUS intensity attenuation. The only basic assumption is that site intensity-ground motion correlations are regionally independent.

One weakness of this approach has to do with apportioning an attenuation model into submodels. The uncertainty contained in each of the submodels increases the uncertainty in the final prediction (Cornell, et al, 1977), although at the present time, there does not appear to be any rational alternative to this.

The added uncertainty significantly influences the seismic hazard results. Greatly improved estimates of the seismic hazard could be obtained through additional work on this topic. When an attenuation model is derived directly from recorded ground motion, the statistical uncertainty usually corresponds to a one-standard deviation level of 1.6-2.0 times the mean. When the uncertainty in mean predictions of intermediate parameters (such as intensity) is rigorously included this multiplicative factor becomes 2.0-2.9 (Cornell et. al, 1977). Clearly, a hazard analysis which integrates out to a 2 or 3 standard deviation ground motion is being driven by this multiplicative factor.

While it has been outside the scope of this effort to address this uncertainty in detail, we believe these uncertainties to be excessive. That is, in spite of their statistical formality, they are derived from data representing all possible earthquake types and all possible travel paths. The seismic hazard at a particular site is usually dominated by a particular type of earthquake (e.g., magnitude range, depth, focal mechanism, etc.), with a particular travel path. We believe that a detailed consideration of this would significantly reduce the attenuation model uncertainty. In the meantime, however, we consider the appropriate value of dispersion to be sufficiently controversial to carry two separate values through our methodology. Our recommended value corresponds to a multiplicative value of 1.82 and accounts for the reduced dispersion associated with the commonality of travel paths, source functions and site effects at each site. We cannot, at this time, provide a quantitative basis for this value; therefore, we are forced to consider another, more conservative value that has a formal statistical basis. Consistent with the uncertainty contained in each of the submodels for attenuation, we also use a value for dispersion of a multiplicative factor of 2.45. A further basis for this particular value is contained in the work done for TVA by Weston Geophysical Inc. (1978). Since dispersion is often expressed as the natural logarithm of this multiplicative factor, these two values can also be expressed as

$$\ln(1.82) = 0.60$$

$$\ln(2.45) = 0.90$$

Another weakness is that the influence of site geology on the predicted site ground motion is more difficult to quantify when the intensity data is incorporated. In the past, several investigators have attempted to quantify site geology effects by including geology (e.g., soil, rock) as a parameter in the regression between ground motion and site intensity. The difficulty in this is that the majority intensity reports are reports for soil conditions at a location nearby an accelerograph station. The conventional procedure has been to adjust the intensity report for the difference in location, and to then associate this adjusted intensity with the recorded ground motion at the accelerograph site. At best, this approach for characterizing site effects is circular, and it results in a systematic bias toward soil response.

Our approach is similar to the one taken by Murphy and O'Brian (1977). Since almost all intensity data correspond to soil intensity data, we assume that a correlation between site intensity and recorded ground motion will be most representative of soil, and that the intensity data alone are inadequate to quantify a corresponding model for rock. We feel that the best way to accurately define a rock model is through Western U.S. data for ground motion as a function of distance, magnitude, and site type. None of the intensity biasing problems discussed above exist for this data set, although we acknowledge potential biases such as building foundation effects (Boore, et. al, 1978). The data currently available are insufficient to resolve at this level of detail, and we, in the end, rely on the overall "reasonableness" of the rock model as a last check. We present the detailed results on our treatment of site geology in a following section, after a summary presentation of the strong motion data base used for analysis.

Summarily, our approach to attenuation is to combine EUS intensity attenuation data with WUS instrumental data relating site intensity to a ground motion parameter. When required for compatibility with a particular expert's input, epicentral intensity is converted to body-wave magnitude. The resulting attenuation model is considered to be appropriate for soil sites. A scale factor is then developed for WUS data for each ground motion parameter to convert the soil prediction to a rock prediction.

4.5 EVALUATION OF SEISMIC HAZARD

Seismic hazard is quantified by the value of a ground motion parameter at the site which is exceeded, with a given probability, in t years. To illustrate this procedure, we shall take the parameter to be peak ground acceleration (PGA). (Identical steps apply to such parameters as peak ground velocity (PGV) and spectral acceleration.)

A typical seismic region contains a number of earthquake sources. Seismic hazard analysis combines the effect of all sources and gives the probability of exceeding a given PGA value at least once during the time-period of interest. The cumulative distribution function of PGA is developed by repeating the process for a number of values.

In the actual process of evaluation, magnitude (M) and intensity parameter (PGA) are discretized into equal-step increments so that all integration operations can be replaced by summations. The earthquake sources are also discretized. The discretization units ("segments") are taken to be small enough that the approximation from continuous to discrete computation is acceptable. The value of λ for a segment is obtained by prorating the λ for the entire source according to the segment area. If an event of magnitude M occurs in a segment at distance R from the site, the probability that $A > a_i$ at the site ($A = PGA$) is readily obtained from the conditional distribution function $F_A(a|M,R)$. In turn, this distribution is obtained from the attenuation relationship and is assumed to be of the lognormal type.

If different events from a given segment have probabilistically independent site effects, then the hazard contribution from segment K over a period of t years is

$$P\left[A > a_i \mid \text{segment } K\right] = \sum_{j_K = 1}^{\infty} \left\{1 - \left[F_A(a_i \mid R_K)\right]^{j_K}\right\} P_{j_K}$$

$$= \underset{j_K}{E} \left\{1 - \left[F_A(a_i \mid R_K)\right]^{j_K}\right\} \qquad (4\text{-}8)$$

in which $F_A(a_i \mid R_K)$ is the CDF of A for an event of random magnitude originated from segment K,

$$F_A(a_i \mid R_K) = \sum_i P_{M_i} F_A(a_i \mid M_i, R_K) \qquad (4\text{-}9)$$

and P_{j_K} = probability of exactly j_K events in t years from segment K.

In the special but important case in which earthquakes from the segment have Poisson occurrence times with mean rate λ_K, Equation 4-8 simplifies to

$$P\left[A > a_i \mid \text{segment } K\right] = 1 - \exp\left\{-\lambda_K t \left[1 - F_A(a_i \mid R_K)\right]\right\} \qquad (4\text{-}10)$$

Combination of hazard contributions from all the segments of all the sources is formally very simple if one assumes independence of site effects from different segments. Equation 4.8 becomes,

$$P\left[A > a_i\right] = 1 - \prod_{\text{all } K} \left\{1 - P\left[A > a_i \mid \text{segment } K\right]\right\} \qquad (4\text{-}11)$$

and for Poisson arrivals,

$$P\left[A > a_i\right] = 1 - \exp\left\{-t \sum_{\text{all } K} \lambda_K \left[1 - F_A(a_i \mid R_K)\right]\right\} \qquad (4\text{-}12)$$

Equations 4-11 and 4-12 give the complementary cumulative distribution of PGA at a site in t years. One typical such function is shown in Figure 4-7.

Once the complementary CDF of A at a site is obtained, one can calculate the value of A which corresponds to any desired probability of exceedance. It has become customary to characterize the hazard level in terms of return period rather than probability of exceedance. This is unfortunate, because the use of return period may be confusing if the earthquake-generating process is nonstationary. A better approach is to fix the time-interval of interest (e.g., the next 50 years) and consider various probabilities of exceedance within that time interval. However, in order to comply with the current trend, we present results also in terms of return period, assuming stationarity. Before deriving the relationship between exceedance probability and return period, we introduce the following definitions:

PROBABILITY OF NONEXCEEDANCE	is the probability that a given level of ground motion will not be exceeded at the site during the period of interest
PERIOD OF INTEREST	is the design life or useful life of a structure or project
RETURN PERIOD (RP)	is the expected time between consecutive events (assuming stationary Poisson occurrences in time)

The following development assumes no statistical uncertainty on the parameters. More complex treatment would be needed to take such uncertainty into account.

Once the period of interest is selected, the probability of nonexceedance which corresponds to any given return period can be calculated by considering the Poisson character of events with site acceleration greater than or equal to a.

The relationship between $P\left[A > a\right]$, period of interest T, and return period RP(a) is

$$P\left[A > a\right] = 1 - e^{-T/RP(a)}$$

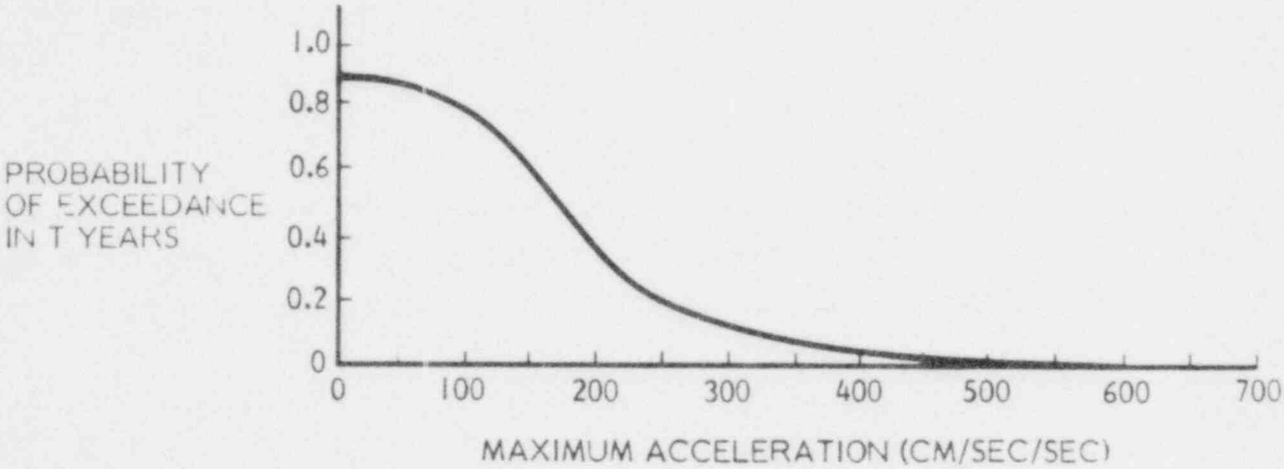


FIGURE 4-7

TYPICAL COMPLEMENTARY CUMULATIVE
DISTRIBUTION FUNCTION OF PGA AT A SITE

Notice that $\lambda(a) = 1/RP(a)$ is the mean occurrence rate of earthquakes that cause peak site accelerations in excess of a.

Thus, if the period of interest is 50 years and a is the acceleration which corresponds to a 200-year return period, the probability of exceeding a in 50 years is

$$P\left[A > a\right] = 1 - e^{-0.005 \times 50} = 0.221$$

The relationship between return period, period of interest, and exceedance probability is plotted in Figure 4-8. Note that accelerations associated with a 200-year return period have a 22% probability of being exceeded in 50 years (as from the preceding calculation). The relationship can be applied whenever the stationary Poisson model of occurrences is appropriate.

For large return periods, the annual exceedance probability can be approximated as 1/RP. It is also interesting to note that the probability of no exceedance occuring in RP years is exactly 1/e = 0.368.

A plot of typical peak site acceleration versus return period is presented in Figure 4-9.

Synthesis of Results

Different seismic hazard evaluations at a site were obtained using information provided by different experts. The parameters considered were PGA, PGV, nine spectral ordinates of the 5% damping response spectrum (at natural periods T = .04, .05, .08, .10, .20, .30, .40, 1.0 and 2.0 seconds), and Modified Mercalli Intensity. A typical set of spectra for the 1,000-year return period is shown in Figure 4-10. Processing each expert's information individually has the advantage of providing a range of results corresponding to the opinions of different experts. If desired, a synthesis result can be obtained through one of several procedures (e.g., by the method of weighted averages, which is described below).

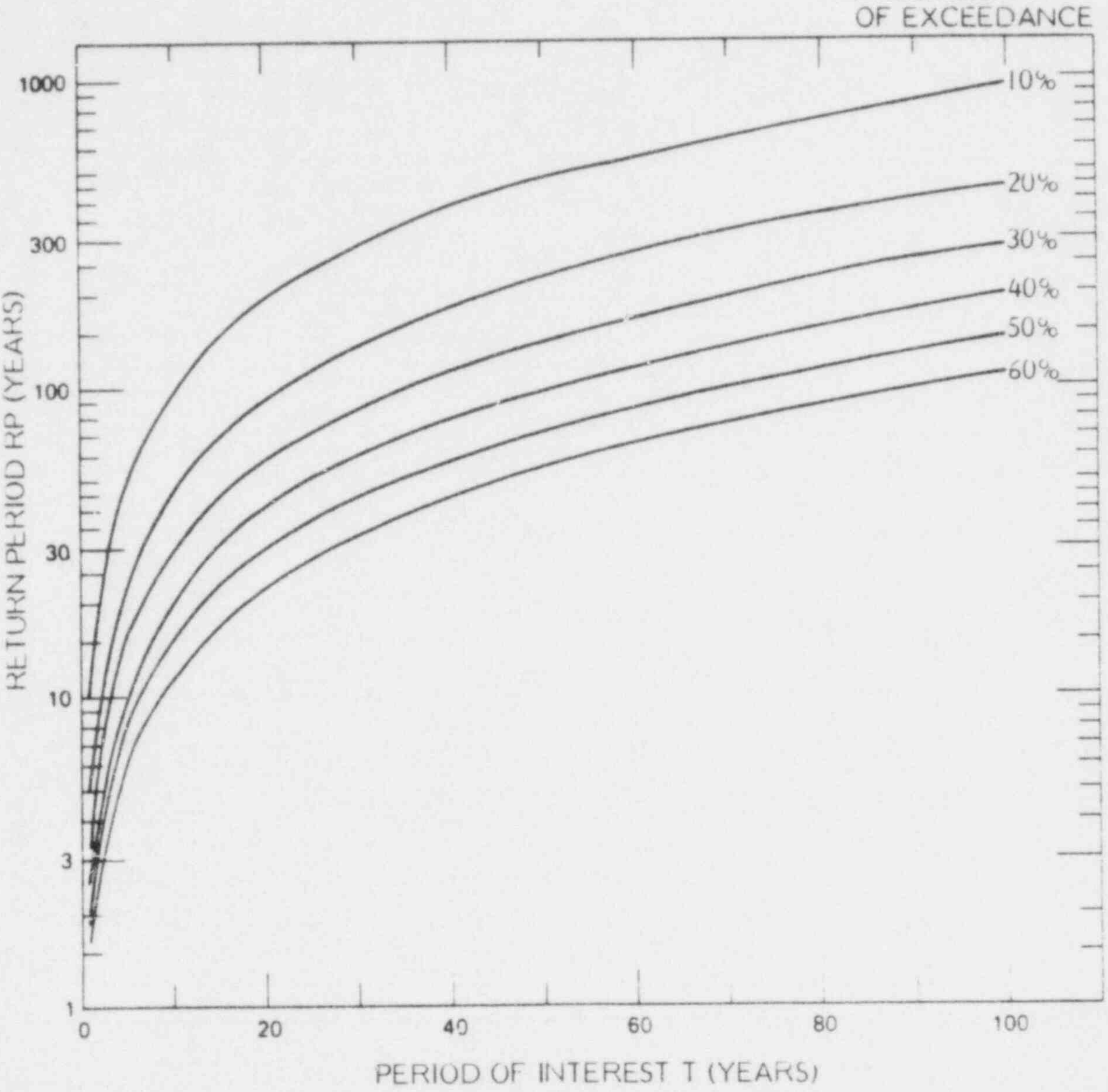


FIGURE 4-8

RELATIONSHIPS BETWEEN RETURN PERIOD RP,
PERIOD OF INTEREST T, AND PROBABILITY
OF EXCEEDANCE, P(A>a)

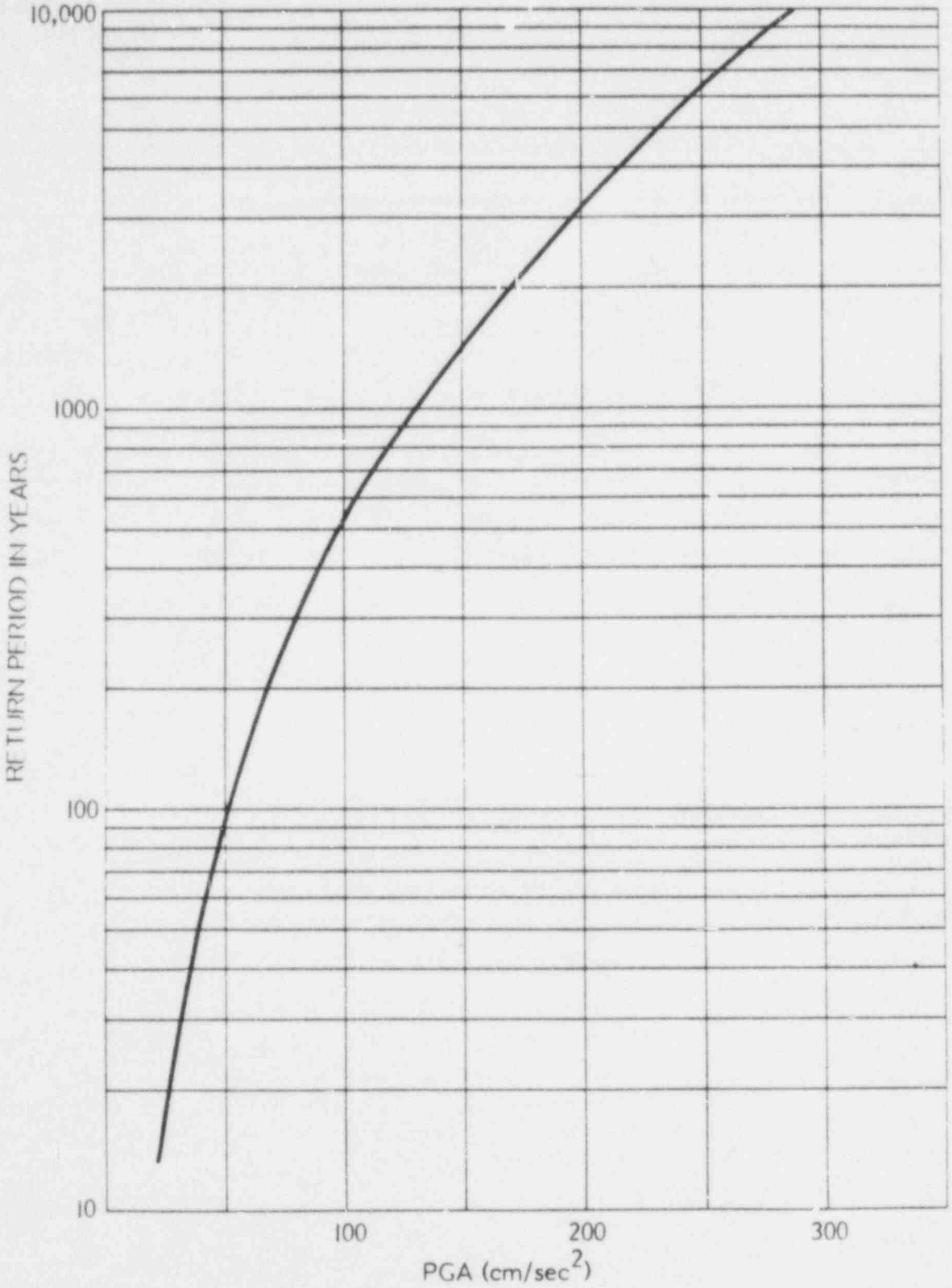


FIGURE 4-9

TYPICAL PLOT OF PGA VS. RETURN PERIOD

1000 YEAR RETURN PERIOD

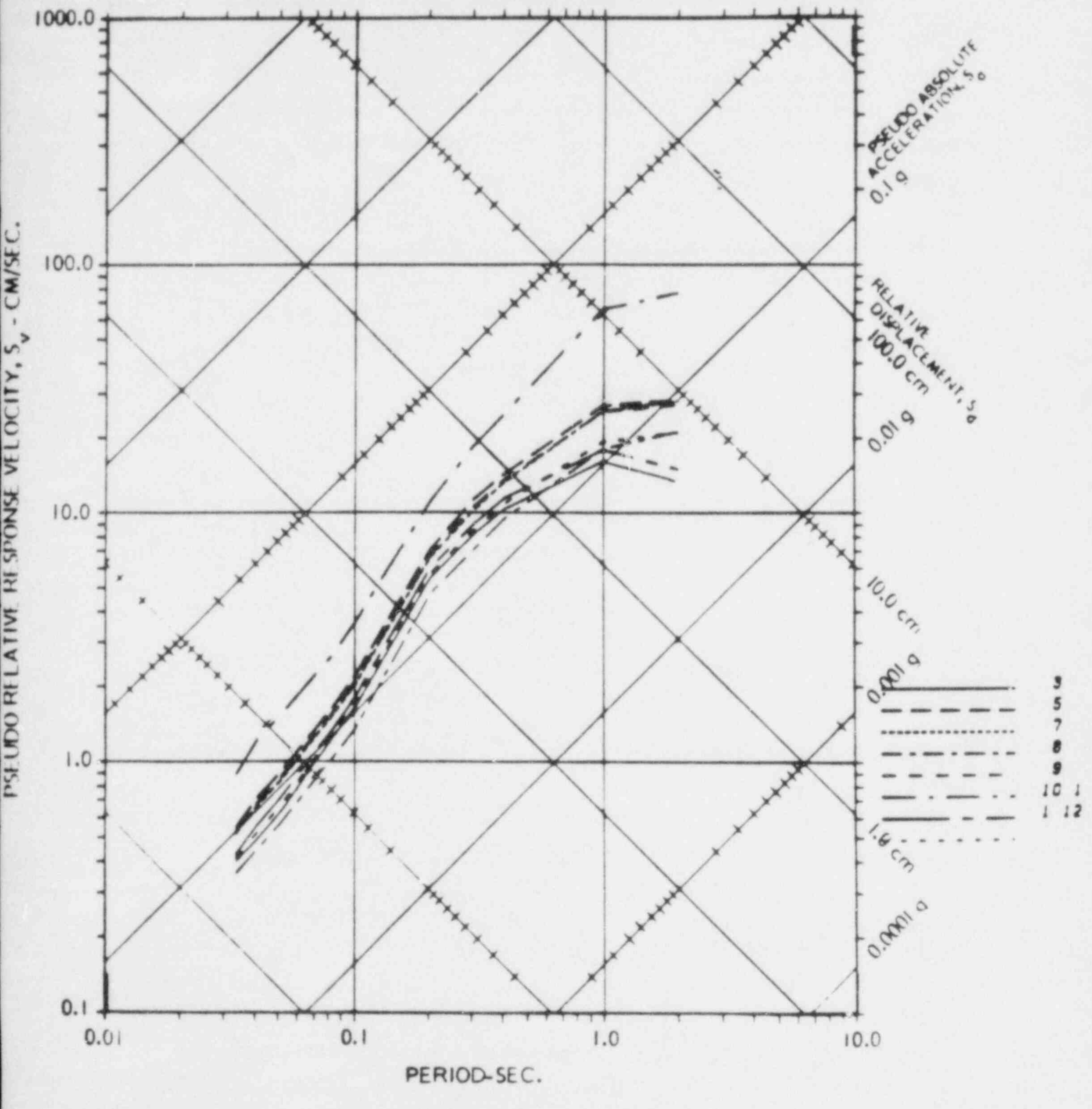


FIGURE 4-10

TYPICAL SPECTRA AT A FIXED SITE
FOR DIFFERENT EXPERTS

(Only 8 experts provided an input for the Central United States)

In the questionnaire, experts were asked to rank themselves on a scale of 0 to 10 with respect to confidence in their answers. For each zone considered, three self-rankings were requested: zonation (R_z), upper magnitude (R_u) and recurrence (R_s).

These rankings (or "weights") and the fraction of hazard contributed by each zone, were used to reach the synthesis. For each expert j, the weight of source i was computed from the self-rankings as

$$W_{ij} = \sqrt{R^2_{z_{ij}} + R^2_{u_{ij}} + R^2_{s_{ij}}}$$

Also, for the return period considered and for each expert, we determined the fraction p_{ij} of hazard contributed by source i. (An example is given in Table 4-1.) Finally, the weight of each expert was computed as

$$E_j = \sum_i p_{ij} \; W_{ij}$$

and the weighted average of a given parameter (L) for a fixed return period was obtained as

$$L_{\text{synthesis}} = \sum_j L_j \; E_j / \sum_j E_j$$

where L_j = value of L for expert j.

Additional development and justification of this combination rule is presented in Appendix D. This process must be repeated for each seismic hazard parameter and return period. Figure 4-11 presents a typical synthesis spectrum.

1000 YEAR RETURN PERIOD

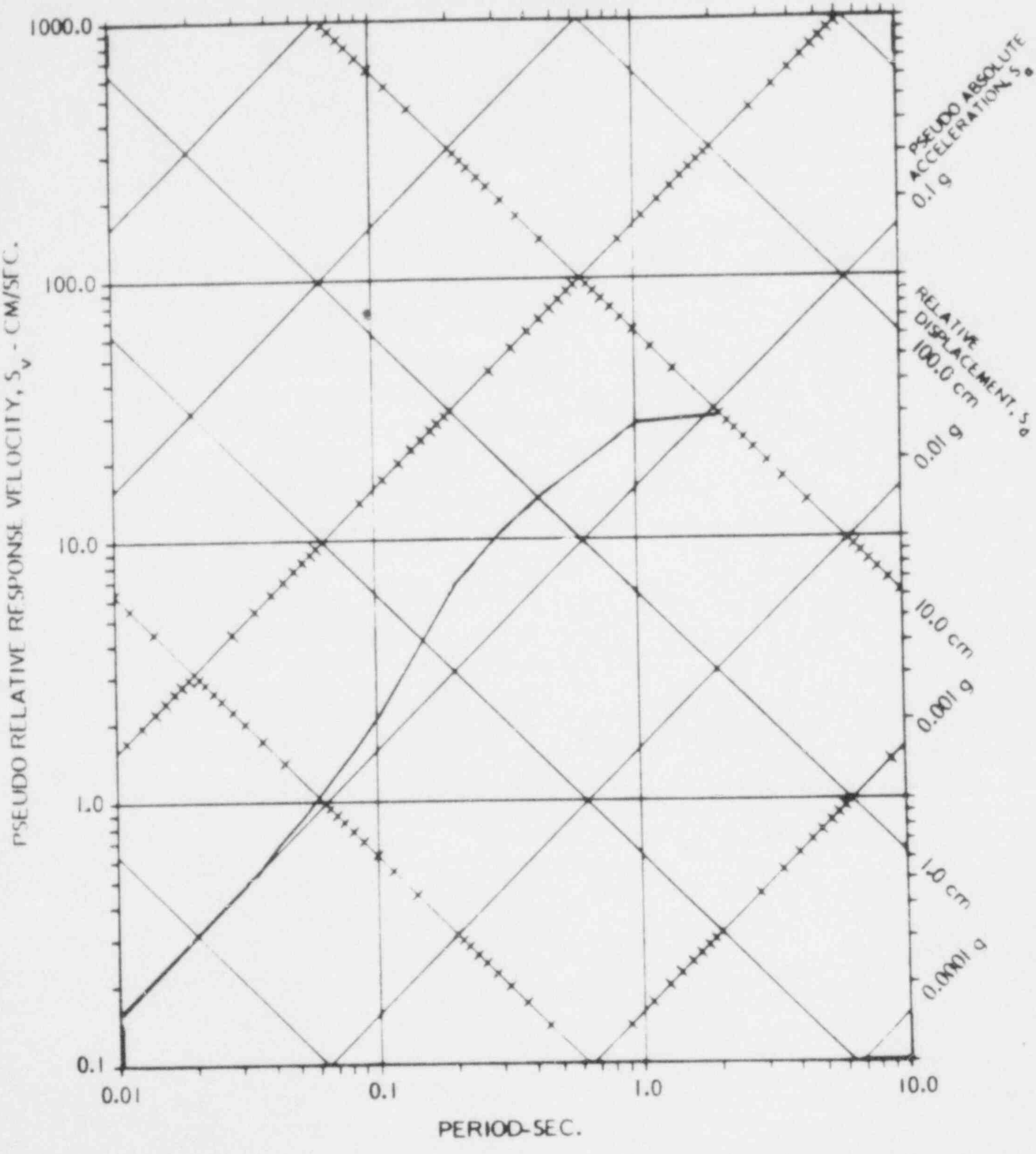


FIGURE 4-11

TYPICAL SYNTHESIS SPECTRUM

TABLE 4-1

SOURCES WEIGHTS AND CONTRIBUTIONS FOR A GIVEN LOADING PARAMETER AND RETURN PERIOD

		Zone Index					
		1		2		i	
Expert	Seismic* intensity	Weight	Contribution (%)	Weight	Contribution (%)	Weight	Contribution (%)
1	L_1	W_{11}	P_{11}	W_{21}	P_{21}	P_{i1}	P_{i1}
2	L_2	W_{12}	P_{12}	P_{22}	P_{22}	W_{i2}	P_{i2}
.							
.							
.							
j	L_j	W_{1j}	P_{1j}			W_{ij}	P_{ij}

---

* L_j = value of a seismic intensity parameter L with a given return period at the site, according to expert j.

5.0 UNIFORM HAZARD SPECTRUM

In order to understand how the uniform hazard spectra (UHS) can be used for design, it is important to consider the definition of UHS and study its implications. A uniform hazard spectrum is developed using probabilistic methods in such a way that each spectral amplitude has the same probability of being exceeded in a given period of time. In its development, each period is considered independently of another, and correlation between the spectral amplitudes is not explicitely taken into account. This comes about for the following reason: when developing the spectrum, predictions are made for one period at a time, say T_1. All the potential earthquakes contributing to the seismicity at the site are then considered using the seismicity, attenuation and exposure models, and their cumulative contribution to the loading at period T_1 is computed as a cumulative distribution function of the loading. The spectral acceleration versus return period plot (Figure 5-1) is then developed and the loading corresponding to the return period (RP) of interest (say 1,000 years) is used as the appropriate spectral amplitude for design at period T_1. The procedure is repeated for other periods within the frequency range of interest and the spectrum is built point by point. Figure 5-2 presents a typical uniform hazard spectrum for two levels of exceedance: 10 and 20 percent.

If we are interested in periods T_1 and T_2, the spectral amplitude corresponding to those periods indeed have the same probability of being exceeded due to all the earthquakes affecting the site. However, it becomes apparent that since each period is treated independently of another, the notion of a specific spectral shape corresponding to a particular earthquake is lost in the process. The consequence of this point is illustrated below for a multi-degree of freedom system.

First, consider a single degree of freedom system. If one is interested in the loading at a single period T_1 only the UHS effectively provides the loading corresponding to the RP of interest since it represents, for that loading, the contribution from all earthquakes affecting the site. This would apply for the design of a system modeled by a single degree of freedom system, such as a piece of equipment.

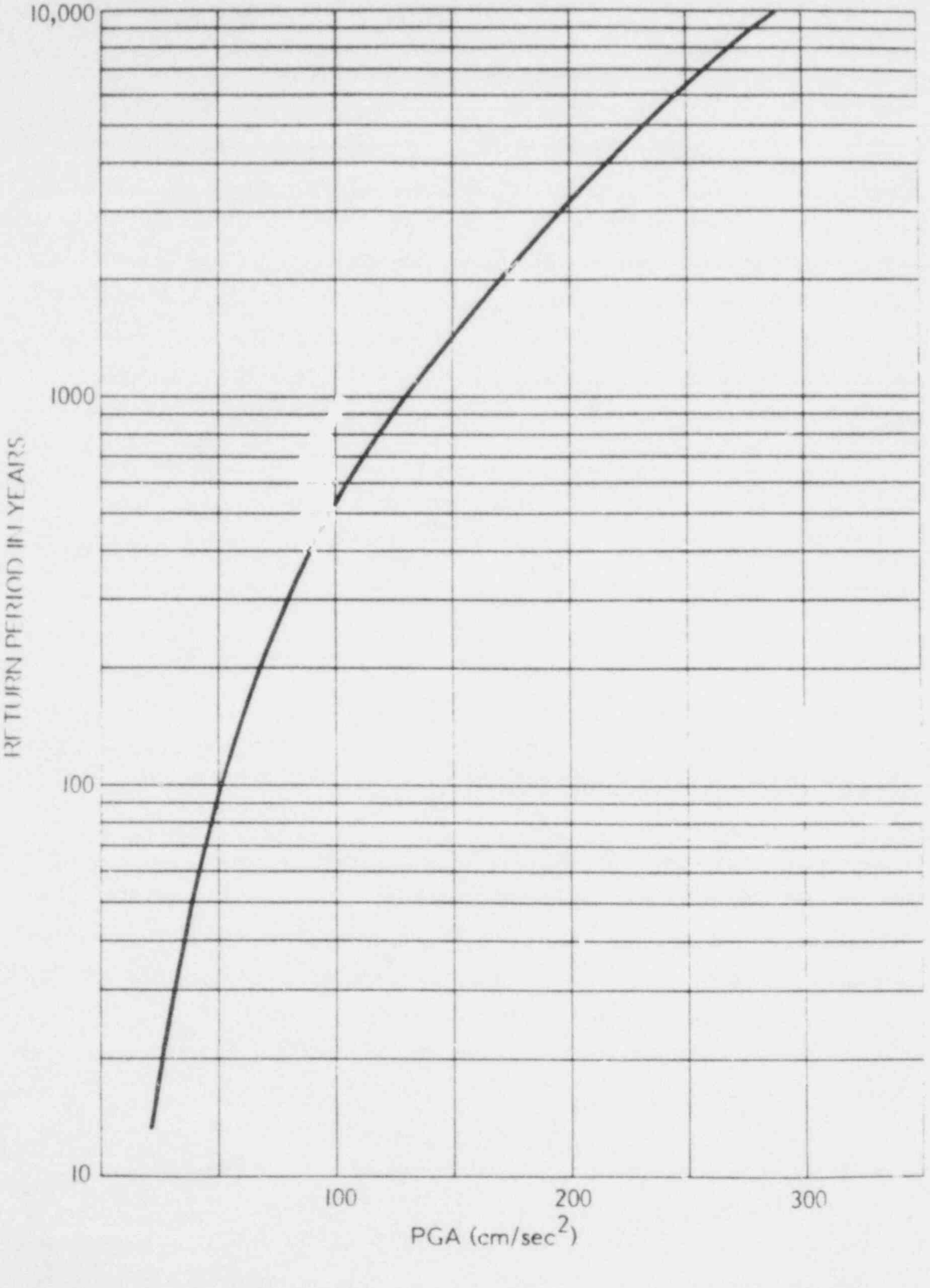


FIGURE 5-1

SPECTRAL ACCELERATION VS. RETURN PERIOD
FOR PERIOD T_1

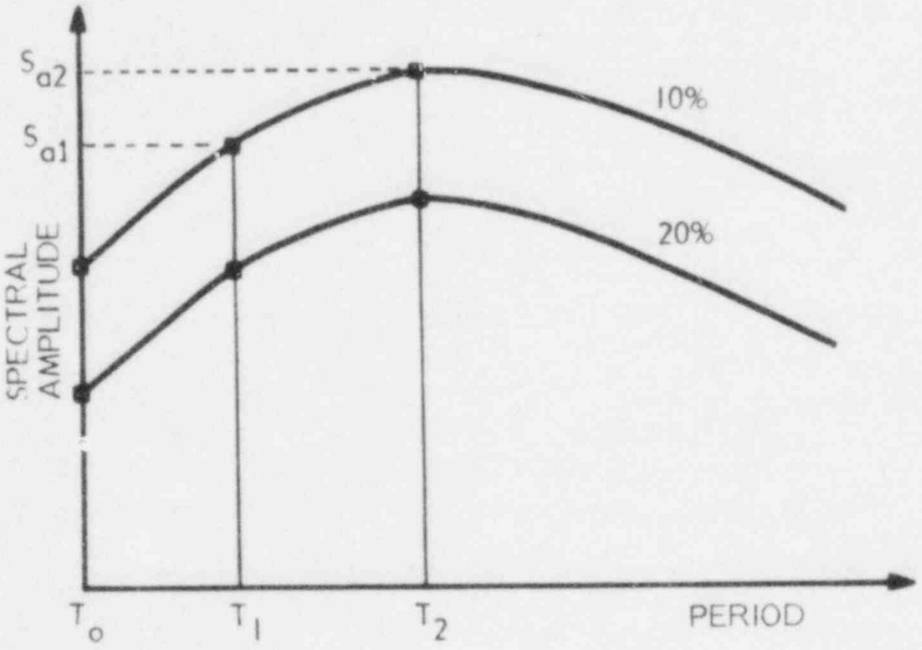


FIGURE 5-2

TYPICAL UNIFORM HAZARD SPECTRA
FOR 10% AND 20% PROBABILITY OF EXCEEDENCE

On the other hand, when one is interested in designing for a multi-degree of freedom system, two characteristics enter the picture that make the UHS a conservative, if not overconservative, design tool. For illustration, let us consider a two degree of freedom system with fundamental periods T_1 and T_2 ($T_1 < T_2$). The UHS amplitude corresponding to T_1 and T_2 are Sa_1 and Sa_2 respectively (Figure 5-2). As is well known, there is a high probability that the loadings Sa_1 and Sa_2 will not be felt by the structure at the same time, i.e., for a given event, the largest acceleration in the response time histories for periods T_1 and T_2 will not occur at the same instant. It is therefore conservative to add the loadings Sa_1 and Sa_2 as if their effect were cumulative. The square root of the sum of the square (SRSS) method of design qualitatively takes this into account by assuming that the global loading is on the average better represented by the vectorial sum of the individual modal loadings.

A more important characteristic is that the UHS is not representative of any single event. If the structure is subjected to a high frequency earthquake, the low frequency content of its spectrum will most probably be small. Conversely, if the event is distant and high in low frequency its spectrum will most probably have little energy in the high frequency range. In other words the spectral amplitudes Sa_1 and Sa_2 will not be felt by the structure for any single event. Since the structure will only have to resist one earthquake at a time, using Sa_1 and Sa_2 in a model superposition analysis is conservative.

The goal is therefore to design for event specific uniform hazard spectra (ESUHS): spectra that correspond to the types of earthquakes that can be felt at the site. There is a large number of such spectra and it is unreasonable to want to consider each of them separately.

From an engineering point of view, it appears reasonable to consider only a few types of spectra, for example: high frequency, intermediate, and low frequency. Since the purpose is to obtain a number of uniform hazard spectra resulting from the sorted contribution of different types of earthquakes, it is necessary to determine the parameters that govern the shape of earthquake spectra in order to assign the contribution of each event to the correct ESUHS.

In a probabilistic hazard analysis, the spectral shape is determined by the attenuation relationships used to transfer the loading information from the generating source to the site. Carrying the discussion for two periods of interest, the attenuation relationship is of the type:

$$Sa\Big|_{M,R} = \frac{b_{11}e^{b_{21}M}}{R^{b_{31}}} \quad \text{at } T_1$$

$$Sa\Big|_{M,R} = \frac{b_{12}e^{b_{22}M}}{R^{b_{32}}} \quad \text{at } T_2$$

The spectral shape (ratio of Sa_1 to Sa_2) varies significantly with distance (Figure 5-3), whereas it only varies marginally with magnitude (Figure 5-4). Hence as a first approximation, a good separator for spectral shapes is distance and only the cumulative exposure from earthquakes within a distance band should be considered to produce an ESUHS. From Figure 5-3 one sees that two or three distance bands would be appropriate.

In order to remain consistent with a global hazard corresponding to a chosen RP, one cannot simply design for the most critical ESUHS at that RP. One has to consider the additional contribution of the others. One approach based on design is presented in the following paragraph.

Let us consider the two periods of interest T_1 and T_2 and assume that the earthquakes susceptible of affecting the site analyzed can be broadly sorted (based on distance) in two types of spectral shapes. For each distance band and period a spectral amplitude versus RP plot is obtained. Figure 5-5a presents separately the spectral amplitude at T_1 corresponding to the nearby and distant earthquakes and a combination of both. Figure 5-5b presents the same curves for period T_2.

Using the modal superposition method, one can determine a load versus RP curve for each ESUHS (Figure 5-5c, $R < R_2$ and $R > R_2$). Assuming independence

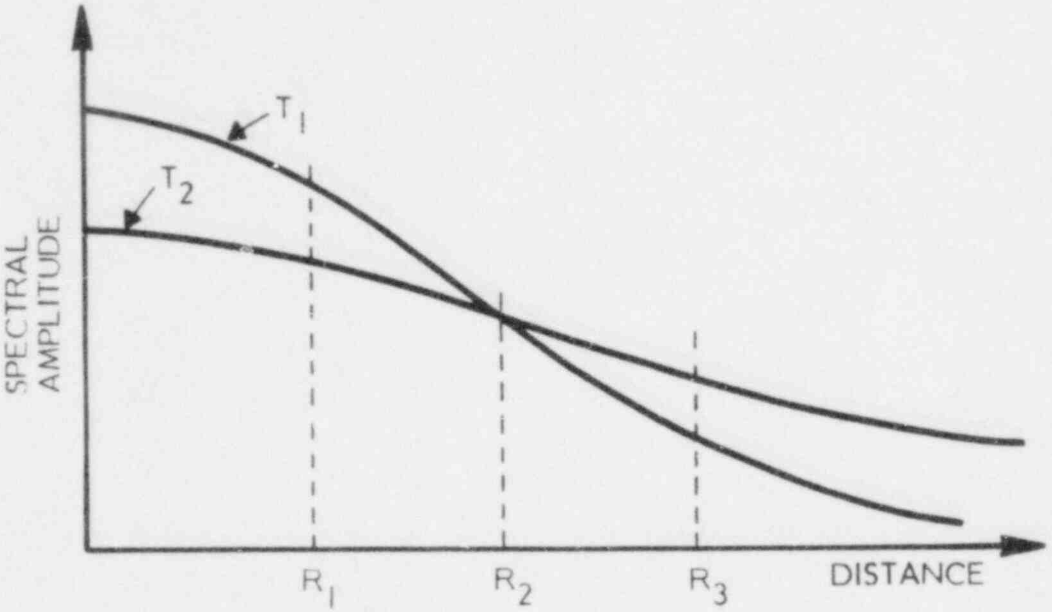


FIGURE 5-3

TYPICAL ATTENUATION OF S_{a1} AND S_{a2} WITH DISTANCE
(FIXED MAGNITUDE)

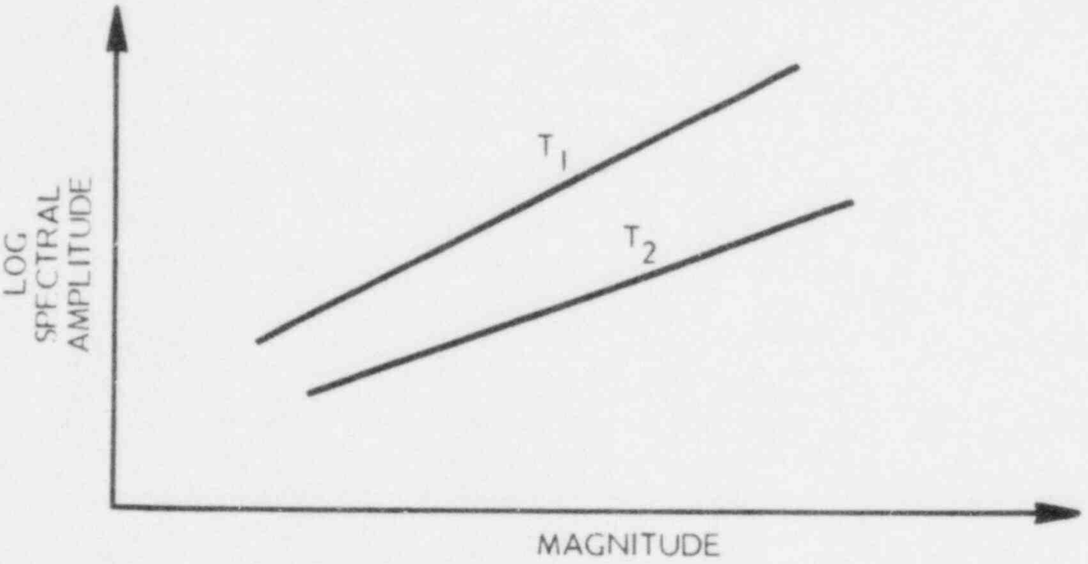
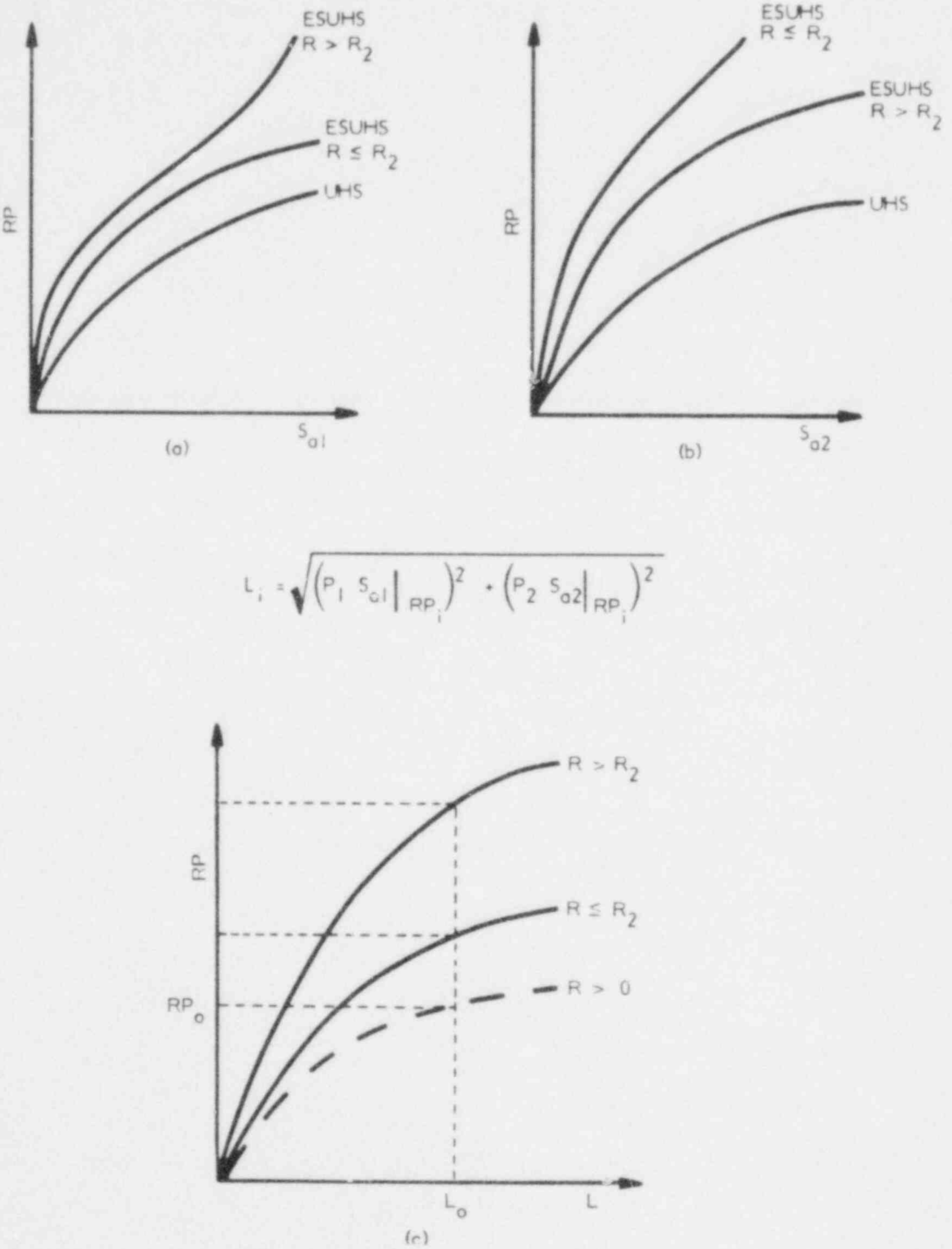


FIGURE 5-4

TYPICAL VARIATION OF S_{a1} AND S_{a2} WITH MAGNITUDE
(FIXED DISTANCE)



$$L_i = \sqrt{\left(P_1\, S_{a1}\Big|_{RP_i}\right)^2 + \left(P_2\, S_{a2}\Big|_{RP_i}\right)^2}$$

FIGURE 5-5

DETERMINATION OF DESIGN LOAD FROM TWO ESUHS between both ESUHS, the global load versus RP is obtained (Figure 5-5c, $R > 0$). This curve presents in terms of a design parameter the global contribution of both nearby and distant earthquakes to the hazard at the site. The load corresponding to RP_o on this last curve represents the value to be used for design. One can see that it corresponds to different RP for each ESUHS load curve.

This approach, which is structure dependent, represents a more rational attempt to take into account the specific spectral shape of earthquakes felt at the site. It removes some of the conservatism implicit in the UHS method.

APPENDIX A

TREATMENT OF SYSTEMATIC AND RANDOM ERRORS

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TREATMENT OF SYSTEMATIC AND RANDOM ERRORS

It is sometimes convenient to think of earthquake events as points in a multidimensional Cartesian space (earthquake space) with coordinates for time (t), for the epicentral coordinates (x,y), and for magnitude (M). If other characteristics at the source of the earthquake process are relevant (length of fault rupture, type of mechanism, stress drop, focal depth, etc.), the dimension of the space should be increased and these characteristics associated with additional coordinate axes. If the times of occurrence form a Poisson process with known intensity $\lambda(t)$, if all other earthquake characteristics (x,y,M) are independent from event to event, and if the distribution of (x,y,M) given t is known, then the point process in earthquake space is nonhomogeneous Poisson, with intensity function $\lambda(t,x,y,M) = \lambda(t) f_{x,y,M \mid t}(x,y,M)$ in which $f_{.}$ = probability density function of (.). All uncertainties of such a model are of the <u>random</u> type, in that the earthquake characteristics (t,x,y,M) are independent from event to event. If the parameters of the attenuation law are known, and if attenuation errors are independent for different events, then the point process of earthquake characteristics at the site (defined in an appropriate space) is also known, and all uncertainties related to this process are random.

In practice, the function $\lambda(t,x,y,M)$ is seldom known; (1) because $\lambda(t)$ is uncertain; (2) because the earthquake source boundaries are uncertain $\left[f_{x,y \mid t}(x,y) \text{ is uncertain}\right]$; or (3) because magnitude distribution parameters (upper bound magnitude, b value, etc.) are not precisely known. In this case, given $\lambda(t,x,y,M)$, the point process in earthquake space is still Poisson. However, when uncertainty on λ is accounted for, the point process is no longer Poisson, but rather, is of the Doubly-Stochastic Poisson type. Uncertainty on parameters that affect the characteristics of <u>all</u> earthquake events (e.g., parameters of the distributions of epicentral coordinates and magnitude) is <u>systematic</u> and requires separate treatment. If a procedure is available for generating seismic hazard results under the Poisson assumption, it should be repeatedly used with different given functions $\lambda(t,x,y,M)$. The conditional seismic hazard distributions should then be weighted by the probability of the associated λ functions, and averaged. A similar procedure should be used to treat (systematic) uncertainty on attenuation parameters and on site effect coefficients. A detailed treatment of the parameters affecting systematic uncertainty follows.

Let $\underline{\theta}_{\text{source}}$ and $\underline{\theta}_{\text{site}}$ be vectors that collect all parameters contributing to systematic uncertainty at the source and at the site, respectively. Thus, the geometry, the mean occurrence rate λ, the frequency-magnitude slope b, and the upper bound magnitude M_U of each source are in $\underline{\theta}_{\text{source}}$, whereas coefficients and residual variance of the attenuation law and site amplification factors are in $\underline{\theta}_{\text{site}}$.

Given $\underline{\theta}_{\text{source}}$, the point process in earthquake space is Poisson and is characterized by an intensity function $\lambda_{\text{source}}(t,x,y,M|\underline{\theta}_{\text{source}})$. If, in addition, $\underline{\theta}_{\text{site}}$ is known, then the point process of earthquakes at the site is Poisson, say with intensity function $\lambda_{\text{site}}(t,I_s|\underline{\theta}_{\text{source}}, \underline{\theta}_{\text{site}})$, in which I_s = MMI or another intensity measure at the site.

Since

$$\underline{\theta} = \begin{bmatrix} \underline{\theta}_{\text{source}} \\ \underline{\theta}_{\text{site}} \end{bmatrix}$$

is uncertain, the functions λ_{source} and λ_{site} are unconditionally random, and the earthquake process at the site is of the Doubly-Stochastic Poisson type. Hazard analysis with earthquake processes of this type requires two steps. First, let A be the value of peak ground acceleration at the site in T years, and calculate $P(A > a|\underline{\theta})$ using the Poisson model with intensity $\lambda_{\text{site}}(t,I_s|\underline{\theta})$. In the second step, remove conditionality on $\underline{\theta}$:

$$P(A > a) = \int_{\text{all } \underline{\theta}} P(A > a|\underline{\theta})\, dF_{\underline{\theta}}(\underline{\theta})$$

Practical implementation of this two-step analysis is often a formidable task, due to the many components of $\underline{\theta}$.

A simplified approach consists of evaluating the sensitivity of $P(A > a)$ to the randomness of each individual component of $\underline{\theta}$, and retaining only the components found to be important. The less important parameters are treated in approximation, either as constant or as independent from event to event.

It may be useful to intuitively evaluate (and, in some cases, with the support of sensitivity analysis) the importance of systematic uncertainty on individual parameters:

1. **Source Configuration:** Let θ be a discrete random variable which attains value $i \ (i = 1, \ldots n)$ if the source has configuration according to hypothesis i. The probability that $\theta = i$ is denoted by P_i; hence,

$$\sum_{i=1}^{n} P_i = 1 \ .$$

   Difference in the exceedance probabilities calculated by the correct procedure

$$P(A > a) = \sum_i P_i \, P(A > a \,|\, \theta = i)$$

   and by the procedure described in Section 4.2 (one Poisson source for each alternative) is expected to be very small.

2. λ **for each source**: Small exceedance probabilities (i.e., probabilities of interest for engineering hazard analysis) are nearly linear functions of λ. This implies that

$$\begin{aligned} P(A > a) &= \underset{\lambda}{E}\Big[P(A > a \,\big|\, \lambda)\Big] \\ &\approx P\Big[A > a \,\big|\, \lambda = E(\lambda)\Big] \end{aligned}$$

Hence, negligible error derives from setting λ equal to its expected value.

3. **Parameters of the magnitude distribution (b and M_U):** Treatment of b and M_U as independent from event to event, rather than constant for all events from a given source, may introduce some error, especially for small site-intensity values. Two hypotheses that should bound the seismic hazard are:

   a. b and M_U independent for different earthquakes (analysis in this report)

   b. b and M_U random but identical (or proportional to given values) for all earthquakes from all sources. In this case, $P(A > a)$ is calculated as

   $$P(A > a) = \underset{b,M_U}{E}\left[p(A > a \mid b, M_U)\right]$$

   For all cases considered by us, the difference between $P(A > a)$ calculated by these two procedures was found to be small. Results from procedure a and from correct analysis (b and M_U the same for all earthquakes from the same source but possibly different for different sources) should differ by even smaller amounts.

4. **Uncertain parameters of the attenuation law:** As in the case of b and M_U, one can incorporate the effect of parameter uncertainty under the assumptions of independent (case a) or perfectly dependent values (case b) for different earthquakes. These assumptions should produce results that bound those generated by more realistic and complicated models. Because the attenuation relationship is a critical element of seismic hazard evaluation, sensitivity to different assumptions may be significant.

5. **Site effects** are conceivably the same for all earthquakes. Their uncertainty is easily incorporated into the analysis through random scaling or shifting of the site intensity parameter.

APPENDIX B

SOLICITATION OF EXPERT OPINION

APPENDIX B

SOLICITATION OF EXPERT OPINION

B.1 BIASES AND MODES OF JUDGMENT

Biases are discrepancies between a subject's answers and his real knowledge Such discrepancies can take several forms. They may affect best estimates, in which case they are called location biases. When biases affect confidence in estimates (e.g., the variance of a parameter), they are called dispersion biases. Their source may be either motivational (the subject modifies answers in his favor) or cognitive (based upon the way in which the subject formulates his judgments) and can be either conscious or unconscious.

Modes of judgment are procedures by which people assess uncertainty. On the basis of laboratory experiments and common experience, Spetzler and von Holstein (1975) noticed three common traits of these procedures:

- People are typically not aware of the cues upon which their judgments are based.
- It is difficult to control the cues which people use in their judgments
- When people are made aware of biases in their judgment, they have some success in correcting them

It is convenient to classify modes of judgments into four categories: (1) representativeness, (2) availability, (3) adjustment and anchoring, and (4) unstated assumptions.

Representativeness. Often a simple event is given more weight than it should be, because it is well defined and considered representative, while the whole population carries more generalized information. The biases resulting from representativeness can often be reduced or eliminated by structuring the problem in more detail (Spetzler and von Holstein, 1975).

Availability refers to the ease with which past occurrences can be brought to mind. For instance, recent events which made a strong impression at the time of occurrence are more readily available (recallable) than events which occurred far in the past or which did not make a strong impression. Bias resulting from limited availability can be removed by encouraging the subject to broadly survey his information base before formulating judgments.

Subjects tend to insufficiently revise their initial judgments after being provided with additional evidence. This phenomenon is called anchoring. Anchoring often occurs when subjects are first asked questions which they consider to be very important. Anchoring of biases can be reduced by formulating questions which the subject will perceive as unrelated.

If there is room for unstated assumptions, the subject will, consciously or not, restrict himself to a limited set of possibilities (those with which he feels most at ease), and will disregard other assumptions in his assessment of uncertainty. This obstacle can be removed by properly structuring the problem and by making sure that the conditions under which probabilities are given are explicitly stated.

B.2 QUESTIONNAIRE ON EUS SEISMICITY

A questionnaire was developed to elicit expert opinion on seismicity and intensity attenuation in the northeastern region of the United States. Because it is difficult, or perhaps impossible, to precisely quantify seismicity parameters in that region (due to limitations of the historical record), experts' judgment was considered crucial. Their opinions were used throughout the seismic hazard analysis.

Our goal in eliciting subjective information was to obtain an accurate representation of the experts' uncertainty about parameters that affect seismic hazard. Not only the "most probable value" was sought in each case, but also, whenever possible, the entire probability distribution. Judgmental probability distributions were arrived at through a two-stage procedure. First, a questionnaire was sent to each expert; later, major inconsistencies or other problems were resolved through personal communication.

Before answering the questionnaire, experts were conditioned to think fundamentally about the problem and about their judgment, and to avoid cognitive biases. This was done in the Introduction to the questionnaire. After scaling (quantification of judgment in probabilistic terms), responses were checked for consistency, and inconsistencies were resolved.

In order to help the respondents in answering the questionnaire, we supplied seismicity data from various source zones in the East. These data were based on an integrated catalog of earthquake events generated by combining various regional catalogs for the East. For each of the zones, experts were supplied with (1) a list of all earthquakes having epicentral intensity of IV or greater, and (2) a table giving the number of occurrences of earthquakes of each Modified Mercalli (MM) intensity from IV through XII.

The following points were emphasized before each respondent filled out the questionnaire:

- The level of confidence each expert had in his answers would be explicitly considered. Therefore, since his input would undergo filtering and weighting when combined with the opinion of other experts, he was asked not to feel reluctant to express non-classical viewpoints.
- Nine sites were specified for analysis and experts were asked to concentrate their efforts on sources whose seismicity might affect these sites, leaving in the "background" sources with negligible contribution.
- Answers were to be based on experience and upon geologic and tectonic considerations, as well as available data.
- The questionnaire was designed to contain redundancy, which was necessary for cross-checking and for establishing consistency of the results. The experts were asked not to try to produce answers consistent with earlier answers, since this would defeat the purpose of redundancy.

- Each expert was asked to concentrate on his area(s) of expertise and to focus on the part of the questionnaire with which he felt most comfortable.

- They were also asked to attempt answers to all questions and to skip only those with which they felt uncomfortable with the format of the question or in which they had no confidence in their ability to answer. Large uncertainty could be expressed through the range of values assigned to each parameter and through the confidence the experts associated with their responses.

The questionnaire was divided into five sections:

- Source Zone Configuration
- Maximum Earthquakes
- Earthquake Occurrence
- Attenuation
- Overall Level of Confidence

In the section on Source Zone Configuration, we were concerned with the geometry of regions that appear to be unique in their potential to generate earthquakes. In particular, we were seeking the definition of regions within which the experts felt future earthquake activity would be homogeneous. As a point of reference, we provided maps giving two possible seismic zonations of the Eastern United States. We asked the experts to carefully review these maps and indicate, where they thought there might be inadequacies, by modifying, deleting or adding zones. The experts were asked to indicate their "degree-of-belief" in each source configuration by estimating the likelihood that seismicity of the source is actually part of the background seismicity for the entire region. We also asked them to identify any localized tectonic structures that might affect seismic hazard at nearby sites and to indicate their "degree-of-belief" in the activity at these features.

The Maximum Earthquake section was divided into two parts. In the first part, we solicited information about the size of the largest event expected to occur in each source during a given interval of time. Since extrapolation of results from short time intervals to very long intervals is controversial due to possible nonstationarity of seismicity, we explicitly considered two distinct time periods. The first one was chosen to be 150 years, this being of the same order as the time period of interest and approximately equivalent to the length of recorded historical seismicity in the East. The second time period was chosen to be 1,000 years, since such a period leaves out uncertainties associated with extremely long-term geological variations, clearly outside our scope.

The experts were also asked to consider the largest event that they might expect to occur within the current tectonic framework in each source zone irrespective of the time period. It was emphasized that they should base their answers not only on recorded data, but also on their beliefs about:

- Whether past history can be used for future predictions
- Whether additional information could be drawn from sources such as tectonics, theoretical studies, similarity with other regions in the world, etc.

In the second part of the section, we asked questions related to the return period of the largest event from each source.

The Earthquake Occurrence section sought information about the magnitude-frequency relationship for each source during the next 150 years. Questions were formulated either in terms of the number of earthquakes expected to occur within that period (for example: 47 in 150 years) or in terms of the mean rate of events per year (e.g., 0.313 per year). Experts were asked to base their answers on historical data and on their own judgment (e.g., as to the validity, quality and completeness of the data). To assist respondents in this task, we provided them with a list, in descending order of intensity, of all historical earthquakes with epicentral intensities IV or greater included in the map, and with a table giving the number of earthquakes for each MMI unit from IV through XII. These tables were not "corrected" for completeness, but rather represented the latest generally available information on location and size of recorded or felt events.

The limited strong motion data in the East and, after appropriate correction, the much more abundant data in the West, can be used to construct intensity attenuation relationships for use at eastern sites. The section on Attenuation was intended to provide general information about the validity of existing attenuation relationships for use in the Eastern United States. Attenuation data were not specifically provided for this task; rather, we asked the experts to rely on their own knowledge about attenuation in this part of the country.

In order to measure the overall confidence of the experts in their own answers, the final section asked them to rate their responses, to different sections of the questionnaire for each source zone, on a scale of 1 to 10. Through this rating, a synthesis of results was reached, in the form of a weighted average with weights based on self-ranking.

Responses to questions about parameter values could be given in any of several ways, all convertible to a usable format for analysis. Acceptable answers were:

- A best estimate only (interpreted as known value)
- A range of values defined by lower and upper bounds and associated with a uniform distribution
- A range of values defined by lower and upper bounds and associated with a non-uniform distribution
- A written discussion

B.4 THE EXPERT PANEL

An obvious keystone to any expert opinion solicitation is the selection of the expert panel. The criterion used for this project was simple; employ as many as possible of the best experts in EUS seismology. Thirteen experts were contacted. Of these, only ten were able to complete the questionnaire. These experts, listed by region, were:

Dr. Robert Herrmann
Dr. Otto Nuttli
Dr. Ronald Street
Dr. Gilbert Bollinger
Dr. Edward Chiburis

Dr. Michael Chinnery
Dr. Richard Holt
Dr. Paul Pomeroy
Dr. M. Nafi Toksöz
Dr. Marc Sbar

APPENDIX C

DATA CORRECTION

APPENDIX C

DATA CORRECTION

It has been observed that the completeness of earthquake records varies with time. In the past, due to low population density and lack of interest in earthquake activity, only large events were recorded. With increased instrumental coverage, intermediate and lesser earthquakes have been recorded with more frequency, producing an apparent increase in seismic activity with time which biases statistics from uncorrected catalogs. Evaluation of the degree of completeness of the available earthquake record is an important step in the analysis of data.

One possibility is to confine analysis to sections of the record that are complete for the earthquakes of interest. The main problem with this approach is that it reduces the size of the useful sample and meaningful statistical averages of large earthquakes cannot be obtained because of their infrequent occurrences (Benjamin, 1968). An alternative is to correct for incomplete reporting. In following this second alternative, we have used the procedure by Stepp (1971) to determine the degree of incompleteness. First, we must determine the subinterval of the record in which the mean rate of occurrence for each intensity class is stable. This mean rate can then be determined from the interval with complete data for each intensity class. A complete treatment of the approach is given in the above quoted reference.

Assuming that earthquakes in each intensity class occur according to a Poisson process, and with n_i the number of events of intensity i in t years, the mean rate of events, with intensity i, λ_i, can be estimated as $\hat{\lambda}_i = n_i/t$. This estimator has standard deviation

$$\sigma_i = \sqrt{\frac{\lambda i}{t}} .$$

Hence, if λ_i is constant in time, σ_i versus t should plot on log-log paper as a straight line with slope -0.5. Systematic departure of the data from this line is an indication of incomplete reporting. This procedure may be used to evaluate the intervals over which the record is complete for earthquakes in different intensity classes.

Since the data cover a large geographical region over which the period of complete recording is not expected to be constant, the analysis was applied separately to two subregions: the central stable region, including the New Madrid area, and the Eastern region. The periods of complete recording are given in Table C-1, together with the scaling factor to be applied to the data recorded during stable years in order to prorate them to 175 years.

A typical graph for uncorrected and corrected data is plotted in Figure C-1. First, the incremental uncorrected data were plotted (squares). The same data were then multiplied by the corresponding scaling factor to obtain a corrected homogeneous data sample for 175 years (triangles). Finally, the corrected cumulative number of earthquakes was obtained (circles). These last points were used, together with other information, to estimate the intercept value "a" for the region considered in these areas when the experts did not (themselves) provide a value.

TABLE C-1

CORRECTION RATIOS TO 175 YEARS

Stable Years		MMI	Scaling Factor	
Central U.S.	Eastern U.S.		Central U.S.	Eastern U.S.
70	70	IV	2.5	2.5
100	100	V	1.75	1.75
100	100	VI	1.75	1.75
150	150	VII	1.17	1.17
175	200	VIII	1.0	0.88
175	200	IX	1.0	0.88
175	200	X	1.0	0.88
175	200	XI	1.0	0.88

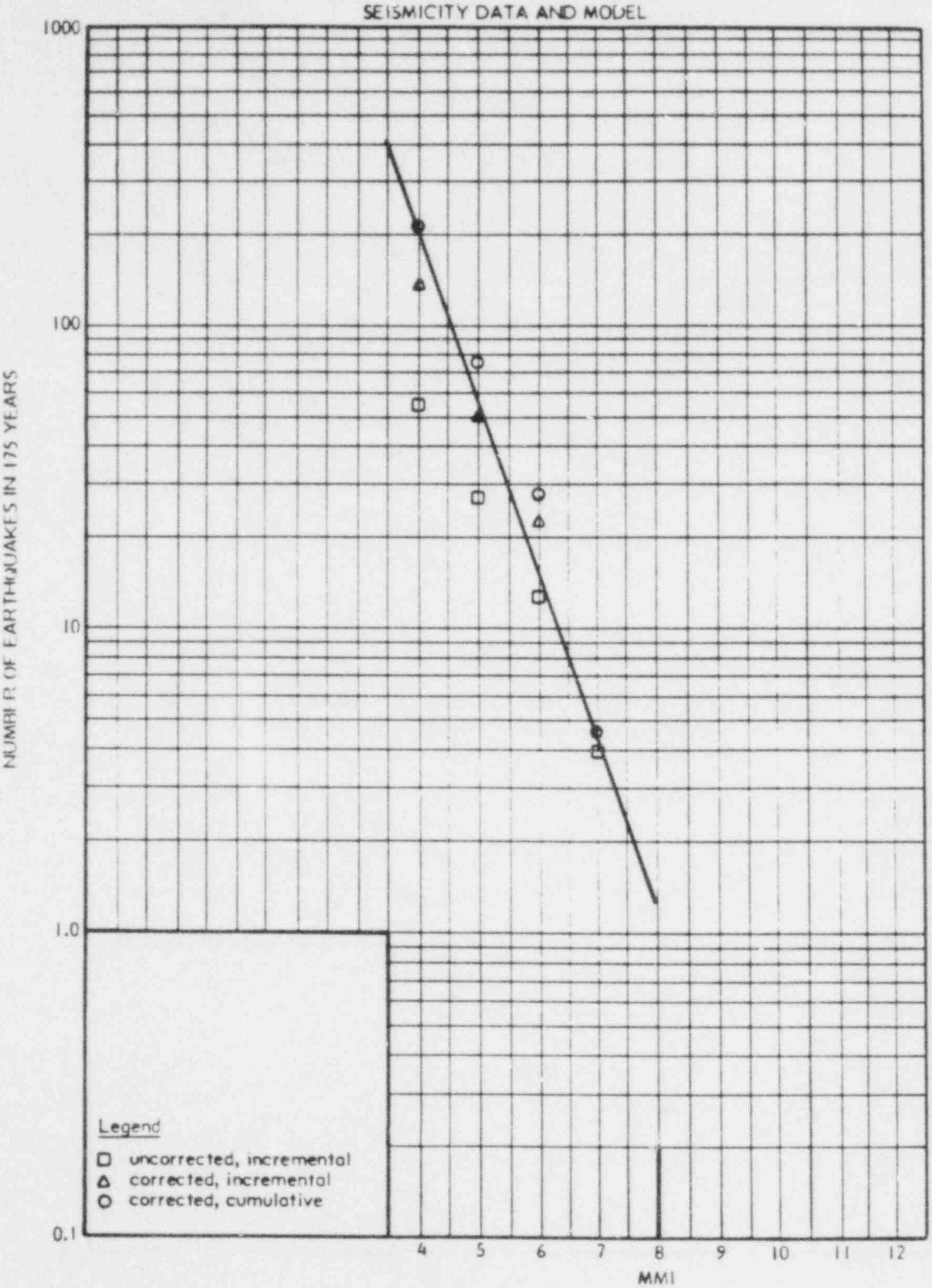


FIGURE C-1

TYPICAL PLOT OF DATA, CORRECTED DATA
AND FITTED RECURRENCE RELATIONSHIP

APPENDIX D

SYNTHESIS OF RESULTS

APPENDIX D

SYNTHESIS OF RESULTS

We first present a theoretical model for combining individual-expert hazard estimates and then introduce the combination rule used in this study.

Theoretical Model

Let A_T be the maximum spectral ordinate at period T over a given time interval and denote by $A_{T,P}$ the P-fractile of A_T, and by A_{T,P_i} the estimate of $A_{T,P}$ using information from the i^{th} expert. The estimation error

$$\epsilon_{T,P_i} = A_{T,P} - A_{T,P_i} \tag{D-1}$$

is assumed to have mean zero and variance, σ^2_{T,P_i}, related to the expert's self-ranking. One should expect errors ϵ_{T,P_i} to be correlated for different values of T or P and also for different experts, due to common factors (same seismic maps and same earthquake catalogs given to all experts, common seismological theories, same seismic hazard analysis procedure, etc.). For given T and P, suppose that the vector

$$\underline{\epsilon}_{T,P} = \begin{bmatrix} \epsilon_{T,P_1} \\ \cdot \\ \cdot \\ \cdot \\ \epsilon_{T,P_N} \end{bmatrix} \qquad (N = \text{number of experts})$$

has mean zero and covariance matrix $\underline{H}_{T,P}$. Then, given the vector

$$\underline{A}_{T,P} = \begin{bmatrix} A_{T,P_1} \\ \cdot \\ \cdot \\ \cdot \\ A_{T,P_N} \end{bmatrix} ,$$

a convenient estimator of $A_{T,P}$ is the so-called (unconditionally unbiased) linear-minimum-variance estimator, $\hat{A}_{T,P}$, which is given by

$$\hat{A}_{T,P} = \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} (\underline{H}_{T,P}^{-1})_{ij} \; A_{T,P_j}}{\sum_{i=1}^{N} \sum_{j=1}^{N} (\underline{H}_{T,P}^{-1})_{ij}} \qquad \text{(D-2)}$$

and has estimation variance

$$\sigma_{T,P}^{2} = 1 / \sum_{i=1}^{N} \sum_{j=1}^{N} (\underline{H}_{T,P}^{-1})_{ij} \qquad \text{(D-3)}$$

In the case when expert estimation errors are uncorrelated, $\underline{H}_{T,P} = \text{diag}\,(\sigma_{T,P_i}^{2})$ and Equations D-2 and D-3 simplify to

$$\hat{A}_{T,P} = \frac{\sum_{i=1}^{N} A_{T,P_i} / \sigma_{T,P_i}^{2}}{\sum_{i=1}^{N} 1 / \sigma_{T,P_i}^{2}} \qquad \text{(D-4)}$$

and

$$\sigma_{T,P}^{2} = \frac{1}{\sum_{i=1}^{N} 1 / \sigma_{T,P_i}^{2}} \qquad \text{(D-5)}$$

In the even more special case when expert estimation errors are uncorrelated and have the same variance σ^2, one finds

$$\hat{A}_{T,P} = \frac{1}{N} \sum_{i=1}^{N} A_{T,P_i} \qquad \text{(D-6)}$$

$$\sigma^2_{T,P} = \sigma^2 / N \qquad \text{(D-7)}$$

These results are consistent with common intuition.

In this study, information could not be elicited directly on the error variances and covariances. Rather, information was obtained in the form of various self-ranking coefficients. Then, a combination rule similar to that used in Equation D-4 was used, i.e.,

$$\hat{A}_{T,P} = \sum_{j=1}^{N} W_j A_{T,P_j} \qquad \text{(D-8)}$$

with weights

$$W_j = \frac{1}{\sigma^2_{T,P_j} \sum_j \frac{1}{\sigma^2_{T,P_j}}} \qquad \text{(D-9)}$$

estimated as:

$$W_j = \sum_i p_{ij} \sqrt{R^2_{z_{ij}} + R^2_{u_{ij}} + R^2_{s_{ij}}} \; . \qquad \text{(D-10)}$$

In Equation D-10, i is a zone index, R_z, R_u, and R_s are the self-ranking parameters, and p_{ij} is the fraction of seismic hazard contributed by i^{th} zone, according to expert j.

The form of Equation D-10 is heuristically correct; e.g., as the self ranking of one expert increases with respect to other experts, the associated weight increases.

Of course, other schemes for combination are possible, within the format of the same theoretical model.

APPENDIX E

ILLUSTRATION OF THE UNIFORM HAZARD METHODOLOGY

APPENDIX E

ILLUSTRATION OF THE UNIFORM HAZARD METHODOLOGY

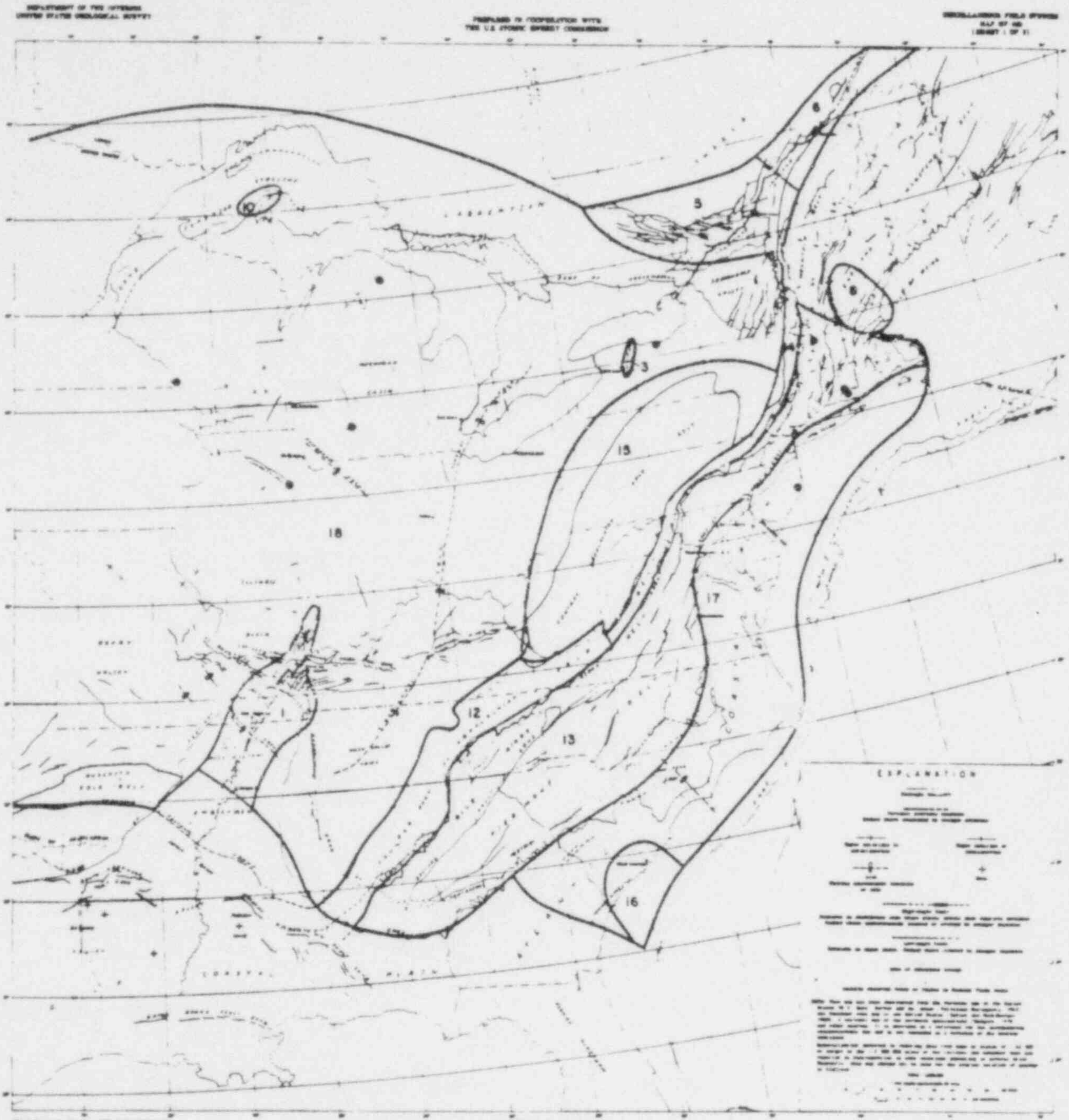
In order to illustrate the various steps of the procedure in Section 4.0, a typical site was selected in the Central Stable Region, and one expert's opinion was processed for input to the analysis.

Application of the hazard procedure consists essentially of defining appropriate input parameters for the source zonation, source seismicity model and attenuation model, and of calculating values of ground motion parameters for various exceedance probability levels. Hence, the output consists of a cumulative probability distribution function for the peak value of each ground motion parameter during a given interval of time. Equivalently, one can give the values of each parameter that correspond to assigned return periods (200 years, 1,000 years and 4,000 years have been used in this analysis).

EXPERT INPUT

After reviewing the two base maps (Figures E-1 and E-2), the expert generated a third map (Figure E-3). Thus, a total of four sources modeled by eight zones were considered to be potential contributors to seismic hazard at the site. Zone numbers, names and areas are given in the first three columns of Table E-1. Column 4 quantifies, on a scale of 0 to 1, the expert's degree of belief (credibility) in the boundaries of each zone. Geometry and credibility of the background sources were not supplied by the expert, since these are calculated by compounding the answers from all experts on the various sources.

Only those events with (epicentral) MMI greater than or equal to IV 1/2 were considered in the analysis, and a 1/2 unit was used as an increment of the discretized intensity scale. (Discretization intervals are centered at IV 1/2, V, etc.). Column 5 gives the cumulative number of events greater than MMI IV 1/4 over a period of 175 years.



A. TECTONIC MAP
SEISMOTECTONIC MAP OF THE EASTERN UNITED STATES
By
Jarvis B. Hadley and James F. Devine
1974

● SITES

——— SEISMIC SOURCE REGION BOUNDARY

TERA CORPORATION

FIGURE 1

POSSIBLE SEISMIC SOURCE REGION CONFIGURATIONS FOR THE EASTERN UNITED STATES

FIGURE E-1

BASE MAP 1

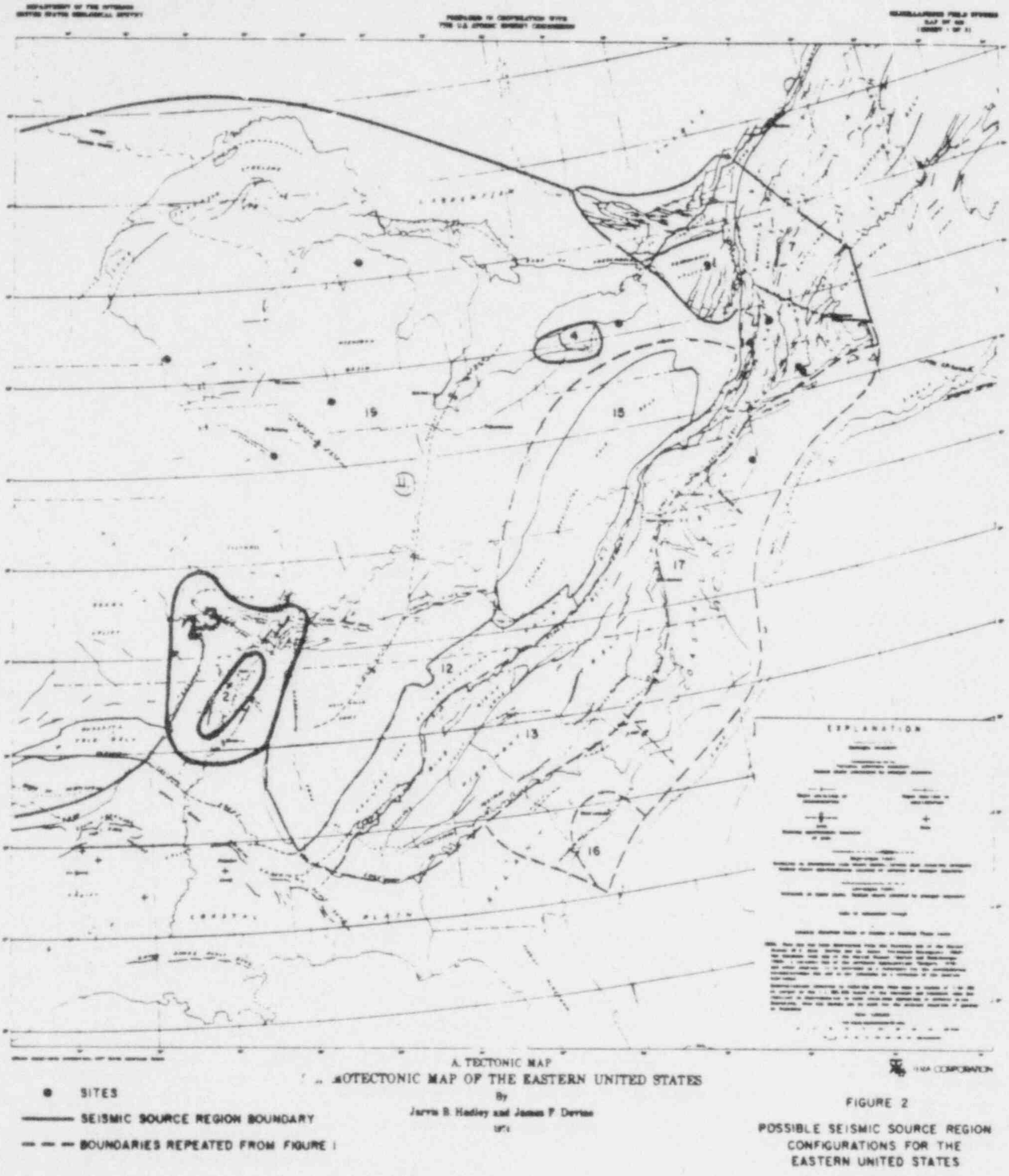
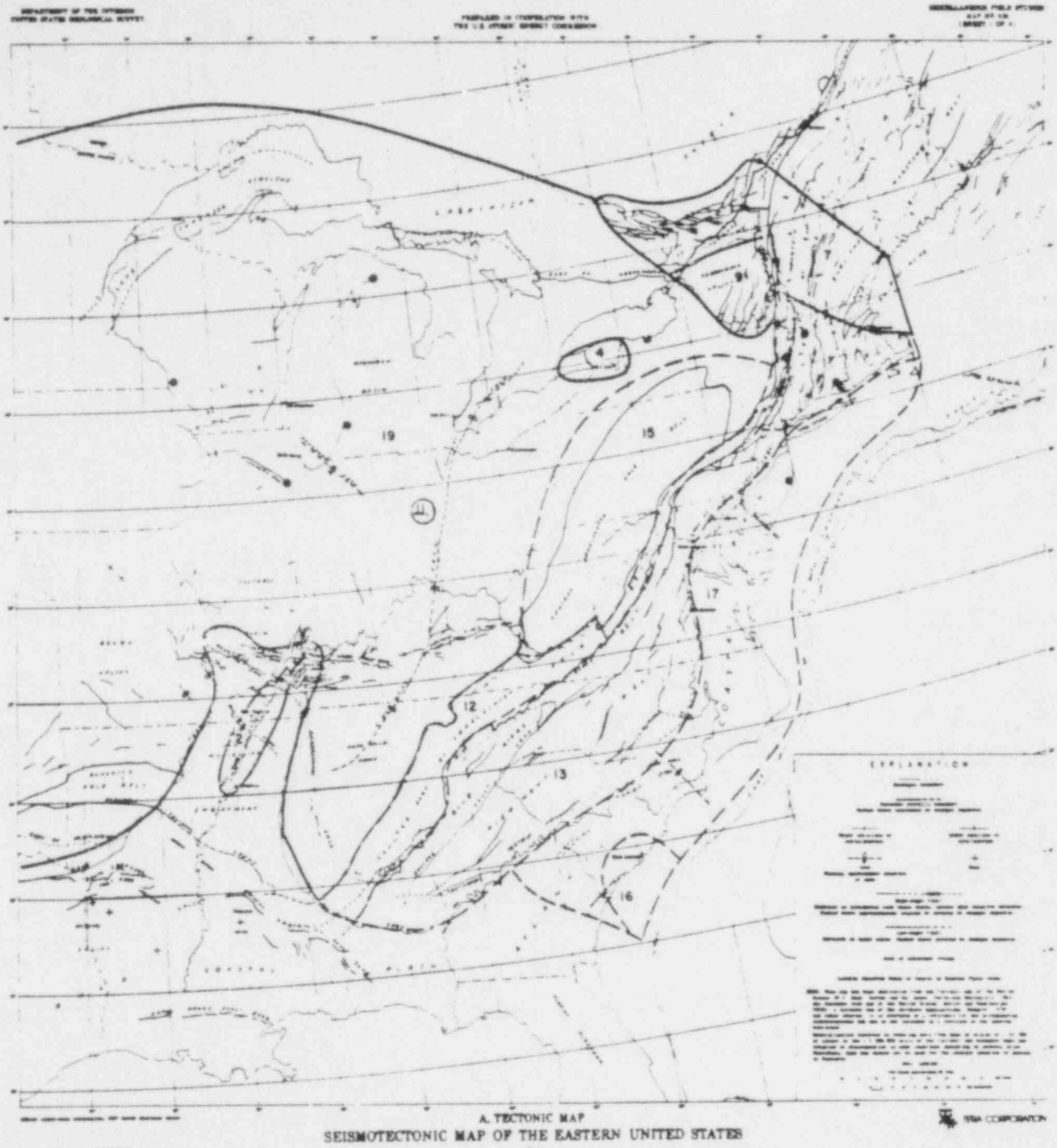


FIGURE E-3

ZONATION MAP EXPERT 11

POOR ORIGINAL



● SITES

——— SEISMIC SOURCE REGION BOUNDARY

— — — BOUNDARIES REPEATED FROM FIGURE 1

FIGURE 2

POSSIBLE SEISMIC SOURCE REGION CONFIGURATIONS FOR THE EASTERN UNITED STATES

FIGURE E-2

BASE MAP 2

TABLE E-1

INPUT FROM EXPERT 11
CENTRAL UNITED STATES

Zone Number	Zone Name	Area (km^2)	Credibility (%)	Number of Events Greater Than MMI = IV½ in 175 Years	Slope MMI	Upper Magnitude Cutoff MMI	Ranking		
							Zonation	Upper MMI	Recurrence
1	New Madrid	55,890	0.60	255	0.50 ± 0.1	XI 1/2-XI 1/2-XII	9	8	7
2	New Madrid (Modified)	16,006	0.85	180		XI 1/2-XI 1/2-XII	9	8	7
23	New Madrid	98,506	0.80 •	160		VI 1/2-VII-VIII 1/2	9	8	7
10	Upper Keweenaw	5,713	0.20	14		VI 1/2-VII-VII 1/2	6	6	4
11	Anna	2,986	0.80	35		VI 1/2-VII 1/2-VIII 1/2	9	7	7
	New Madrid Background	258,056	--	380		XI 1/2-XI 1/2-XII	9	8	7
	Anna Background					VI 1/2-VII 1/2-VIII 1/2			
	Central Stable Region	1,463,550	--	185		VI 1/2-VII 1/2-VIII 1/2	8	6	6

The next two columns (6 and 7) of Table E-1 provide information about parameters of the MMI distribution (slope and upper MMI cutoff). As can be seen from the table, uncertainty on the slope is the same for all sources, whereas uncertainty on the upper MMI cutoff (range and most probable value) is not. The last three columns give the self-ranking by the expert regarding configuration, upper MMI cutoff, and occurrence relationship for each zone.

This expert provided no "a" or λ value for any of the sources. Therefore, these values were obtained by first correcting the data for incompleteness, then fitting a truncated exponential relationship, using the central b value given by the expert ($b = 0.5$ in all cases). Figures E-4, E-5 and E-6 show the uncorrected and corrected data, and the analytical fit for three sources.

TREATMENT OF UNCERTAINTY ON THE DISTRIBUTION OF MMI

Uncertainty on the slope parameter b was treated as described in Section 4.0. Specifically, the parameters ξ_i and η_i of the beta distribution for the probability content of the i^{th} intensity interval were obtained as follows. Given that an event occurs, the probability that MMI falls inside the interval centered at VIII 1/2 (this value corresponds to $m_b = 6$) is 0.0093, 0.0044, and 0.0020 for $b = 0.4$, 0.5, and 0.6, respectively. Hence, the mean, the standard deviation and the parameters ξ and η for that interval are estimated as

$$\begin{aligned} \text{mean probability content} &= 0.0044 \\ \text{variance of probability content} &= (0.00365)^2 \\ \xi &= 1.43 \\ \eta &= 326 \end{aligned}$$

The parameter η is taken to be the same for all intervals, whereas ξ changes, being

$$\xi_i = 326P_i$$

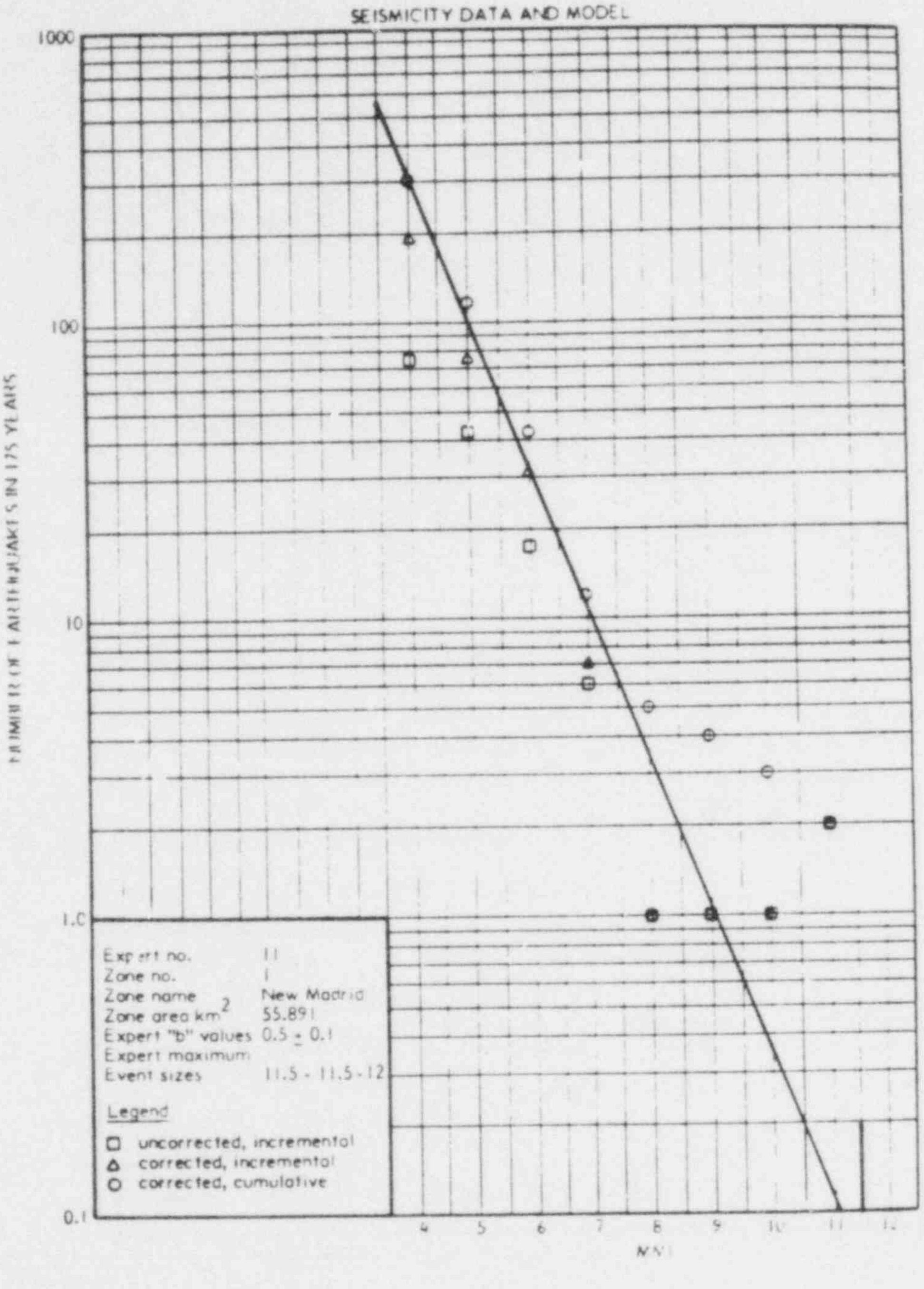


FIGURE E-4

RECURRENCE RELATIONSHIP

EXPERT 11

POOR ORIGINAL

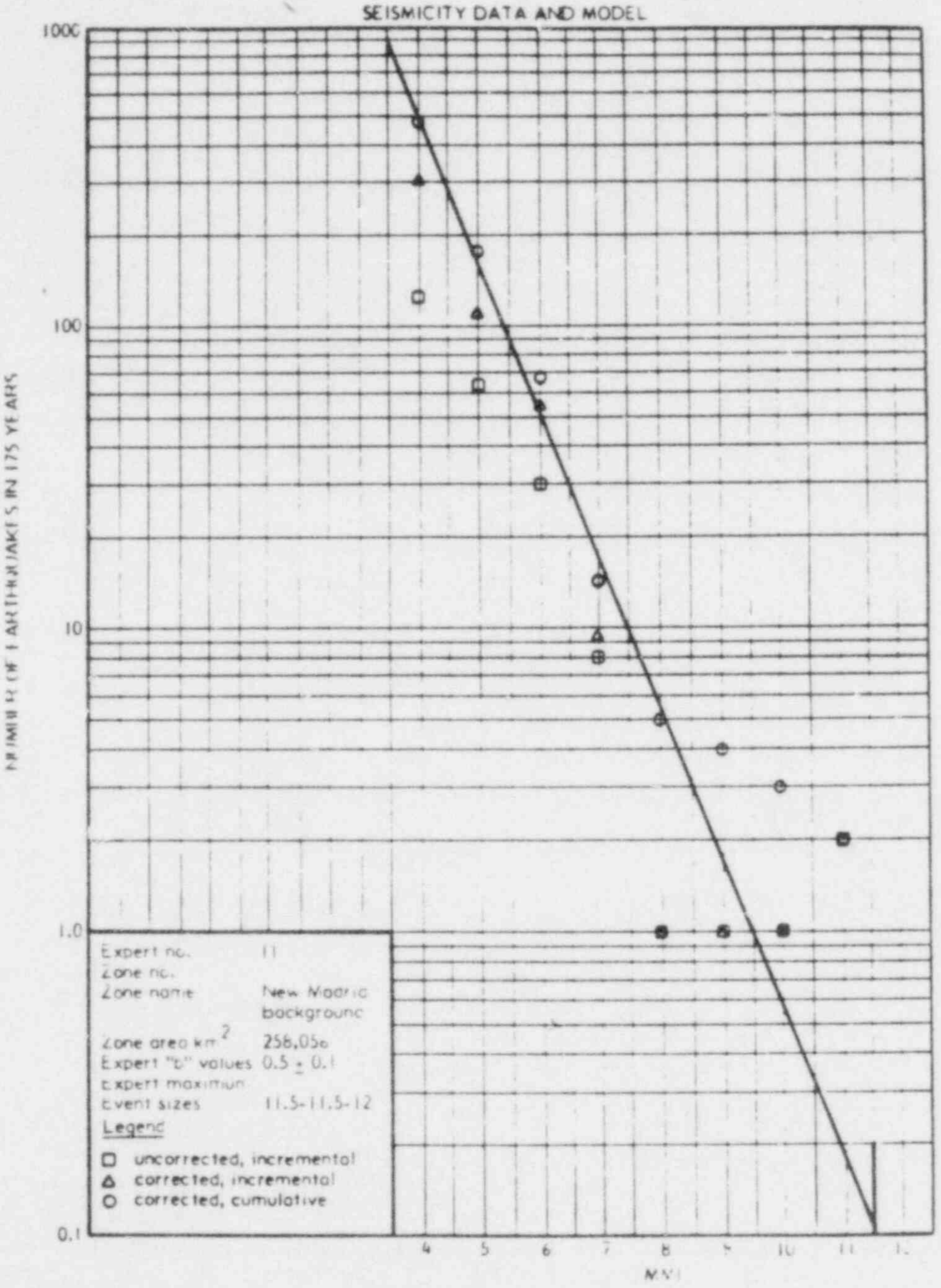


FIGURE E-5

RECURRENCE RELATIONSHIP

EXPERT 11

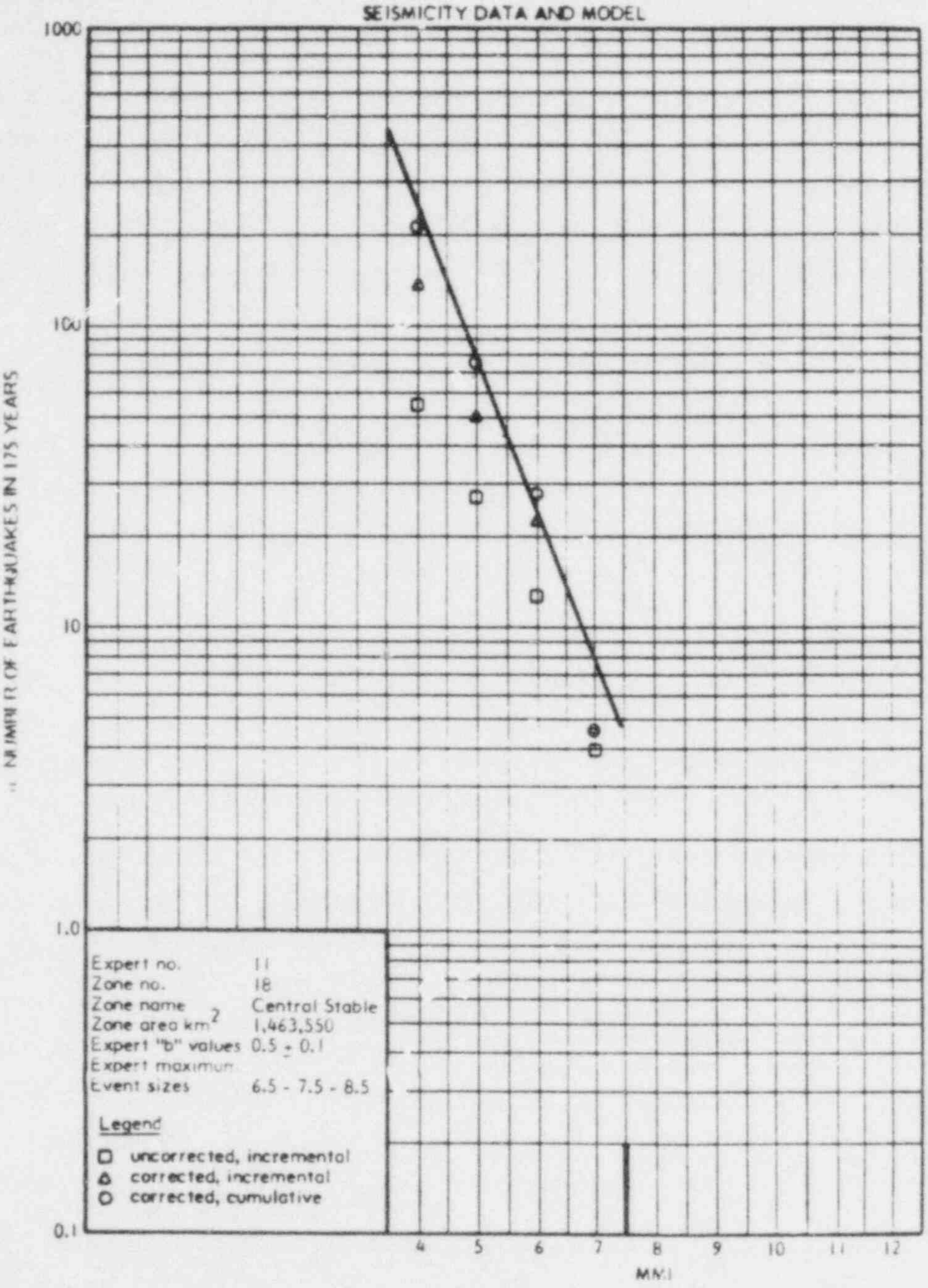


FIGURE E-6

RECURRENCE RELATIONSHIP

EXPERT 11

for the i^{th} interval, with P_i the probability that the generic event has intensity inside that interval if $b = 0.5$. Values of ξ obtained by the procedure are listed in Table E-2.

For Source I, the expert assessed the <u>upper magnitude cutoff</u> to be between m_b 7.5 and 7.75, of which 7.5 is also the most likely value. Using the conversion formula $MMI = 2m_b - 3.5$, MMI becomes XI 1/2 - XII. After fitting a triangular distribution to this range, the following discrete probabilities were found:

$$P\left[MMI_u = XI\ 1/2\right] = 2/3$$
$$P\left[MMI_u = XII\right] = 1/3$$

A similar procedure was used for the other sources. Finally, the values of the parameter ξ in Table E-2 were revised to account for the upper bound intensity in each source.

CALCULATION OF PARAMETERS λ_i', λ_i''

Following the procedure presented in Section 4.0, the seismicity is distributed among alternative zones. The results are summarized in Table E-3. Zones 2 and 23 are treated together since they together represent one alternative to Zone 1. Columns 2 and 3 of Table E-3 present the credibilities of the zones and their corresponding probabilities. The probabilities of the backgrounds are computed as described in Section 4.0. Column 4 presents the number of events assigned to each zone as a function of their probabilities. This number is then modified proportionately to each zone's area to prevent double counting of earthquakes when zones extend under one another. (This is always the case for the background.) Finally, a number of earthquakes from the zones are allowed into their respective backgrounds in proportion to the background's probability. The resulting number of events associated with each zone is tabulated in Column 5. The earthquakes of Zones 2 and 23 are then distributed between

TABLE E-2

DISTRIBUTION EARTHQUAKE MMI

MMI Band	Number of Events
4.5	142.7
5.0	80.3
5.5	45.1
6.0	25.4
6.5	14.3
7.0	8.03
7.5	4.51
8.0	2.54
8.5	1.427
9.0	0.803
9.5	0.451
10.0	0.254
10.5	0.143
11.0	0.0803
11.5	0.0451
12.0	0.0254

TABLE E-3

DISTRIBUTION OF SEISMICITY AMONG ZONES

Zone	Credibilities	Probabilities	λ'_i	λ''_i
1	0.6	.42	142.8	101.4
2 and 23	0.825	.58	197.2	185.1
New Madrid Background		.07		93
10	.2	.2	2.8	2.7
11		.8	28	27.7
Anna Background		.2		6.9
Central Stable Region				116

Zone 2 and Zone 23 in proportion to their original seismicities (98.0 and 87.1 respectively).

The final seismic input is presented in Table E-4.

For the second zonation interpretation (no background), the only zones input in the analysis are Zones 2, 23, 10, 11 and the Central Stable Region. The parameters used for these zones are the ones presented in Table E-1, and no modifications are applied to them.

ATTENUATION

An attenuation model for the Eastern United States was developed, as described in Section 4.0, and used uniformly at all sites and for all experts. It is of the form

$$\ln(GM) = C_1 + C_2 I_o + C_3 r + C_4 \ln r + \epsilon$$

in which GM stands for the ground motion parameter (PGA, PGV, or spectral acceleration at one of nine different frequencies between 0.5 Hz and 25 Hz). The details associated with this model are reported upon in the companion report on results. The attenuation error, ϵ, is assumed to have normal distribution with mean zero and variance σ. The distribution is assumed truncated on either side of the mean at two standard deviations.

SEISMIC HAZARD CALCULATION AND SENSITIVITY ANALYSIS

Using the above information, probability distributions for peak values of ground motion parameters at the site were calculated. For example, Figure E-7 shows a plot of PGA versus return period. A uniform hazard spectrum for 5 percent damping and 1,000-year return period is plotted in Figure E-8.

TABLE E-4

CENTRAL U.S. - EXPERT NO. 11

Zone No.		Zone Name	No. of Events 4.25 MMI in 175 Years	Slope MMI	Upper Magnitude Cutoff MMI
TERA	Expert				
1		New Madrid	101.4	0.50 ± 0.1*	XI 1/2-XI 1/2-XII
2	20	New Madrid	98.0		XI 1/2-XI 1/2-XII
10		Upper Keweenaw	2.7		VI 1/2-VII-VIII 1/2
11		Anna	27.7		VI 1/2-VII 1/2-VIII 1/2
23	23	Mississippi	87.1		VII 1/2-VIII 1/2-IX 1/2
--		New Madrid Background	93.5		XI 1/2-XI 1/2-XII
--		Central Stable Region	116.0		VI 1/2-VII 1/2-VIII 1/2
--		Anna Background	6.9		VI 1/2-VII 1/2-VIII 1/2

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* For all zones.

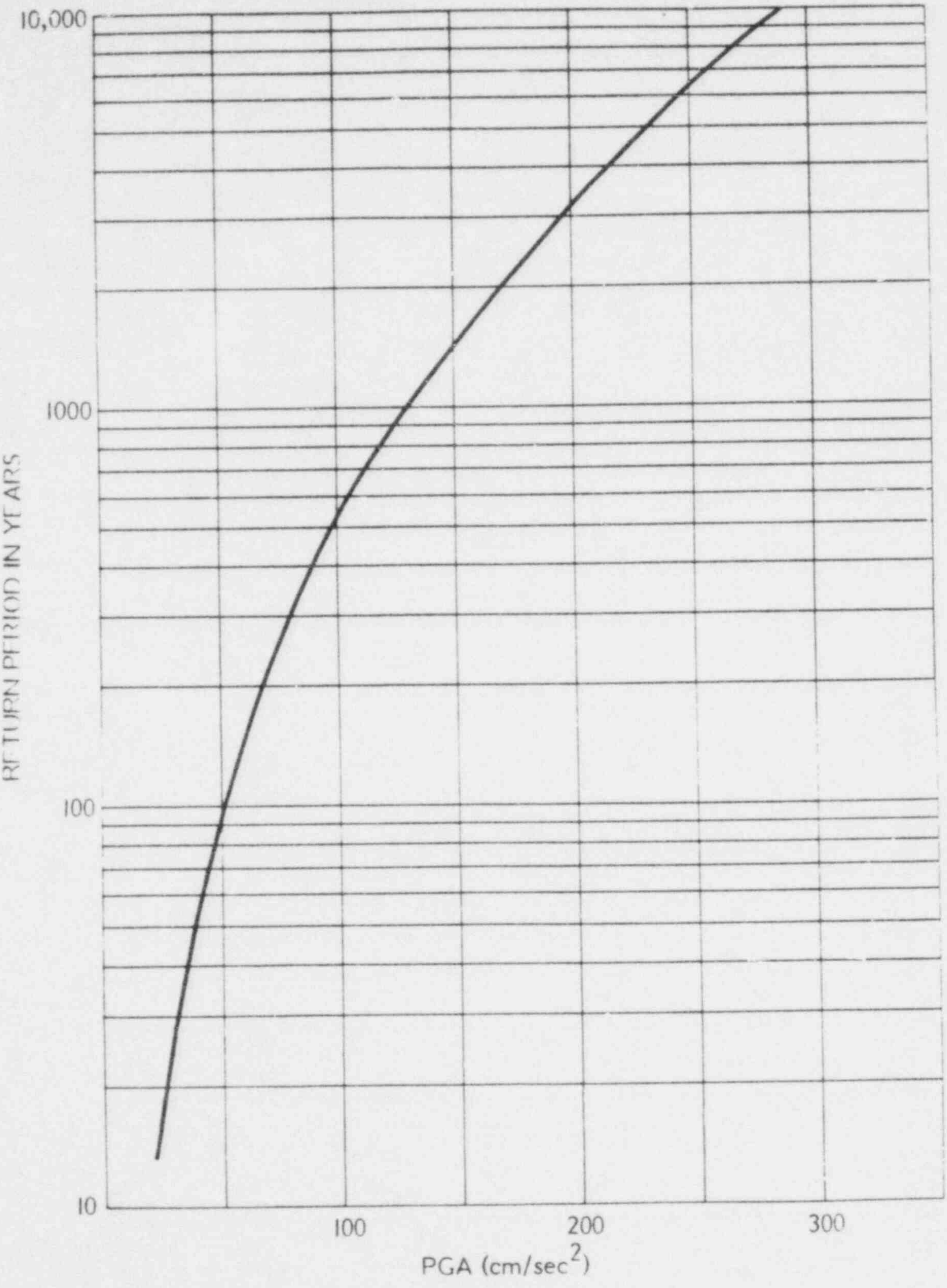

FIGURE E-7

PLOT OF PGA VS. RETURN PERIOD
FOR EXPERT 11

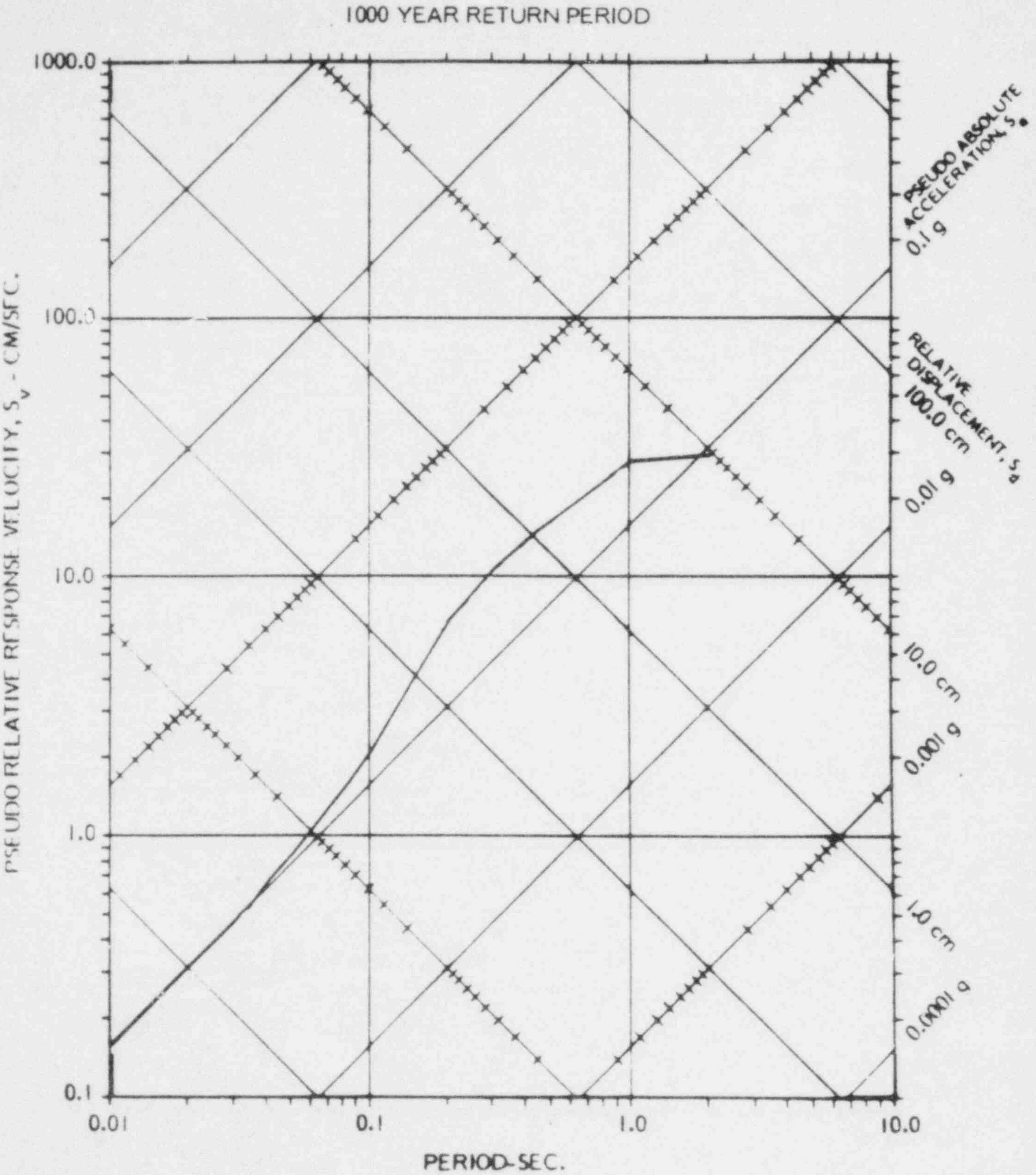

FIGURE E - 8

UNIFORM HAZARD SPECTRUM
FOR EXPERT 11

Results such as provided in Figures E-7 and E-8 depend on a number of factors (source zonation, seismicity, attenuation) which are not precisely known. Sensitivity analysis is a useful tool in assessing the importance of various sources of uncertainty and in identifying the most important parameters.

SENSITIVITY ANALYSIS

Extensive sensitivity studies have been performed and are presented elsewhere. The following comments are of a general nature.

Zonation

The sensitivity of the results to the "background" versus "no background" zonation is a function of the credibilities assigned to the zones, the location of the site and the attenuation law. If the credibility of any one zone modeling a source is high, the probability of the background is low, few events are allowed in it and its effect as a zone is marginal. On the other hand, if the credibility of all the zones is low, the probability of the background is high and it may become the major zone for that source. In the present analysis the background probabilities were seldom greater than 20 percent.

When the site is located away from a major source, the introduction of the background allows larger events to occur closer to the site, and increases the hazard. On the contrary, when the site is located within a highly seismic zone the background, by allowing the distribution of the seismicity over a larger area, decreases the hazard. All the sites considered in this study are located away from major sources. The ground motion model has an effect, too, as slow attenuation and large uncertainty introduce greater contribution of distant zones to the hazard. In this analysis the background zonation gave higher results than the no background zonation by a factor of 10 to 25 percent.

Upper Magnitude Cutoff

The sensitivity of the results to the Upper Magnitude Cutoff is a function of the site of the largest event, the slope of the recurrence relationship and the return period of interest. If the return period is short, the large events do not contribute significantly to the hazard. Similarly, if the recurrence slope is steep the probability of occurrence of large events becomes so low that an increase in upper magnitude cutoff modifies the results only marginally. On the other hand, for long return periods (greater than 5,000 years) and gentle b slope the modifications become significant.

Ground Motion Model

In all hazard analysis procedures, the form of the attenuation relationship and, in particular, the distribution of the attenuation error are critical factors. The shape of the attenuation is usually critical in the middle and far field in determining the contribution of distant sources to the hazard. For the same mean attenuation law, the results are also very sensitive to the uncertainty distribution (sigma value and truncation).

For a fixed number of sigmas, a variation of the value of sigma has a multiplicative effect on the results. Conversely, for a fixed value of sigma, the variation in the number of sigmas has an asymptotically decreasing effect since the added probability of exceedence decays as the tail of the log normal distribution.

APPENDIX F

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APPENDIX F

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This report presents a probabilistic approach for estimating the seismic hazard in the Central and Eastern United States. The probabilistic model (Uniform Hazard Methodology) systematically incorporates the subjective opinion of several experts in the evaluation of seismic hazard. Subjective input, assumptions and associated hazard are kept separate for each expert so as to allow review and preserve diversity of opinion.

The report is organized into five sections: Introduction, Methodology Comparison, Subjective Input, Uniform Hazard Methodology (UHM), and Uniform Hazard Spectrum. Section 2, Methodology Comparison, briefly describes the present approach and compares it with other available procedures. The remainder of the report focuses on the UHM. Specifically, Section 3 describes the elicitation of subjective input; Section 4 gives details of various mathematical models (earthquake source geometry, magnitude distribution, attenuation relationship) and how these models are combined to calculate seismic hazard. The last section, Uniform Hazard Spectrum, highlights the main features of typical results.

Specific results and sensitivity analyses are not presented in this report.

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