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Title: Revision of Seismic and Geologic Siting Criteria

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ABSTRACT

In September of 1990, the U.S. Nuclear Regulatory Commission (NRC) began the formal process to revise the seismic and geologic siting criteria for nuclear power plants. This process is now complete and the revised criteria have been promulgated. During the course of the revision, two draft versions were issued for public comments and extensive interactions took place between the NRC and the industry. This paper describes the new siting criteria and associated regulatory guidance.

1.0 INTRODUCTION

The U.S. seismic siting regulation, "Seismic and Geologic Siting Criteria for Nuclear Power Plants," Appendix A to 10 CFR Part 100, became effective in December, 1973 (Ref. 1). Although it has been a relatively successful licensing tool for over two decades, significant difficulties have been encountered in applying it. For example, there have been substantial advances in the geosciences, and because of the inherent inflexibility of a regulation, it has been difficult or impossible to accommodate these changes or to modify the criteria. Furthermore, Appendix A is based on deterministic seismic hazard concepts, and the large uncertainties intrinsic to geosciences such as seismic sources and ground motions, are not quantitatively taken into account.

Attempts to revise the regulation were started as early as 1979. Ref.2 document the major issues involved and provided strong justification to revise the regulation. However, it was not until 1990 that official revision of Appendix A began.

During the period 1990 through 1995 the proposed regulations and draft guidance documents were prepared, and the new methodologies they invoked were developed and tested. From the onset, it was decided that Appendix A to 10 CFR Part 100 would be retained and continue to apply to operating plants that received their licenses prior to publication of the new regulation.

In developing the new regulation, it was decided to separate siting from design. Therefore, the engineering portions of Appendix A were transferred to 10 CFR Part 50 in a new Appendix S (Ref.3).

The geosciences portion of Appendix A was condensed to general requirements only. The prescriptive elements were placed in Regulatory Guide 1.165 (Ref.4). The new regulations, Section 100.23 to Part 100 (Ref.5), Geologic and Seismic Siting Factors, and Appendix S to Part 50 were published in December 1996 with the effective date of January 10, 1997. The regulatory guides were published in March 1997. The new regulations and guides are applicable to future plants.

2.0 REVISED SEISMIC AND GEOLOGIC SITING AND EARTHQUAKE ENGINEERING CRITERIA

2.1 Siting Criteria

The revised seismic and geologic siting regulation, 10 CFR 100.23, requires that geological, seismological, and engineering characteristics of a site and its environs be investigated in sufficient scope and detail to permit an evaluation of the proposed site, to provide sufficient information to determine the Safe Shutdown Earthquake Ground Motion (SSE), to permit engineering solutions to geologic and seismic effects, to assess the potential for surface deformations, and to establish the design bases for seismically induced floods and water waves, and other design conditions at the proposed site.

Selected portions of the rule are reproduced below. With respect to the intent of the regulation, the rule states the following:

> *§ 100.23 Geologic and seismic siting factors.*
>
> *This section sets forth the principal geologic and seismic considerations that guide the Commission in its evaluation of the suitability of a proposed site and adequacy of the design bases established in consideration of the geologic and seismic characteristics of the proposed site, such that, there is a reasonable assurance that a nuclear power plant can be constructed and operated at the proposed site without undue risk to the health and safety of the public.*

With respect to the specific requirements, the rule contains the following elements:

> ***(c) Geological, seismological, and engineering characteristics.*** *The geological, seismological, and engineering characteristics of a site and its environs must be investigated in sufficient scope and detail to permit an adequate evaluation of the proposed site, to provide sufficient information to support evaluations performed to arrive at estimates of the Safe Shutdown Earthquake Ground Motion, and to permit adequate engineering solutions to actual or potential geologic and seismic effects at the proposed site. The size of the region to be investigated and the type of data pertinent to the investigations must be determined based on the nature of the region surrounding the proposed site. Data on the vibratory ground motion, tectonic surface deformation, nontectonic deformation, earthquake recurrence rates, fault geometry and slip rates, site foundation material, and seismically induced floods and water waves must be obtained by reviewing pertinent literature and carrying out field investigations. However, each applicant shall investigate all geologic and seismic factors (for example, volcanic activity) that may affect the design and operation of the proposed*

nuclear power plant irrespective of whether such factors are explicitly included in this section.

*(d) **Geologic and seismic siting factors**. The geologic and seismic siting factors considered for design must include a determination of the Safe Shutdown Earthquake Ground Motion for the site, the potential for surface tectonic and nontectonic deformations, the design bases for seismically induced floods and water waves, and other design conditions as stated in paragraph (d)(4) of this section.*

(1) Determination of the Safe Shutdown Earthquake Ground Motion. The Safe Shutdown Earthquake Ground Motion for the site is characterized by both horizontal and vertical free-field ground motion response spectra at the free ground surface. The Safe Shutdown Earthquake Ground Motion for the site is determined considering the results of the investigations required by paragraph (c) of this section. Uncertainties are inherent in such estimates. These uncertainties must be addressed through an appropriate analysis, such as a probabilistic seismic hazard analysis or suitable sensitivity analyses. [Underline added for emphasis]. Paragraph IV(a)(1) of Appendix S to Part 50 of this chapter defines the minimum Safe Shutdown Earthquake Ground Motion for design.

(2) Determination of the potential for surface tectonic and nontectonic deformations. Sufficient geological, seismological, and geophysical data must be provided to clearly establish whether there is a potential for surface deformation.

(3) Determination of design bases for seismically induced floods and water waves. The size of seismically induced floods and water waves that could affect a site from either locally or distantly generated seismic activity must be determined.

(4) Determination of siting factors for other design conditions. Siting factors for other design conditions that must be evaluated include soil and rock stability, liquefaction potential, natural and artificial slope stability, cooling water supply, and remote safety-related structure siting. Each applicant shall evaluate all siting factors and potential causes of failure, such as, the physical properties of the materials underlying the site, ground disruption, and the effects of vibratory ground motion that may affect the design and operation of the proposed nuclear power plant.

A comparison of 10CFR 100.23 with Appendix A to Part 100 will clearly show that the new rule contains only the basic requirements and all of the prescriptive procedures are now removed. The requirements for adequate site characterization are basically the same as those in Appendix A, therefore, the geological and seismological investigations are equally important. One of the most significant changes is underlined above. The rule now recognizes that there are uncertainties in estimating the design basis ground motion and they should be specifically addressed in that determination. A probabilistic hazard analysis is permitted to address these uncertainties.

2.2 Earthquake Engineering Criteria

Another important change is with respect to the Operating Basis Earthquake (OBE) in the new Appendix S to Part 50. The existing regulation in Appendix A to Part 100 states that the maximum vibratory ground motion of the OBE be at least one half the maximum vibratory ground motion of the Safe Shutdown Earthquake ground motion. In some cases, for instance piping, this requirement for the OBE made it possible for the OBE to have more design significance than the SSE. A decoupling of the OBE and SSE has been suggested in several documents (e.g., Ref.2). Appendix S allows the value of the OBE to be set at (i) one-third or less of the SSE, where OBE requirements are satisfied without an explicit response or design analyses being performed, or (ii) a value greater than one-third of the SSE.

where analysis and design are required. There are two issues the applicant should consider in selecting the value of the OBE: first, plant shutdown is required if vibratory ground motion exceeding that of the OBE occurs, and second, the amount of analyses associated with the OBE. An applicant may determine that at one-third of the SSE level, the probability of exceeding the OBE vibratory ground motion is too high, and the cost associated with plant shutdown for inspections and testing of equipment and structures prior to restarting the plant is unacceptable. Therefore, the applicant may voluntarily select an OBE value at some higher fraction of the SSE to avoid plant shutdowns. However, if an applicant selects an OBE value at a fraction of the SSE higher than one-third, a suitable analysis shall be performed to demonstrate that the requirements associated with the OBE are satisfied.

As stated, it is determined that if an OBE of one-third or less of the SSE is used, the requirements of the OBE can be satisfied without the applicant performing any explicit response analyses. In this case, the OBE serves the function of an inspection and shutdown earthquake. Three regulatory guides, RG 1.12, RG 1.166, and RG 1.167 were prepared to describe the methodologies acceptable to the staff that should be employed to satisfy the Appendix S requirements pertaining to plant shutdown and restart due to a seismic event.

3.0 GUIDANCE ON DETERMINING SAFE SHUTDOWN EARTHQUAKE GROUND MOTION

Regulatory Guide 1.165 has been developed to provide general guidance on procedures acceptable to the NRC staff for conducting geological, seismological, and geophysical investigations; identifying and characterizing seismic sources; conducting probabilistic seismic hazard analyses; and determining the Safe Shutdown Earthquake Ground Motion (SSE) for satisfying the requirements of 10 CFR 100.23.

The following is an abbreviated discussion of the step-wise procedure outlined in the guide to determine the SSE at a site. This procedure is schematically illustrated after describing the steps.

1. Regional and site geological, seismological, and geophysical investigations should be performed.
2. For central and eastern US (CEUS) sites (sites east of the Rocky Mountains), the Lawrence Livermore National Laboratory (LLNL) (Ref.6) or the Electrical Power Research Institute (EPRI) (Ref.7) Probabilistic Seismic Hazard Analysis (PSHA) should be performed using original or updated sources (based on the investigations performed in Step 1). For sites in other parts of the country, a site-specific PSHA should be accomplished. The ground motion estimates should be made for rock conditions in the free-field or by assuming hypothetical rock conditions for a non-rock site to develop the seismic hazard information base.
3. Using the reference probability (RP) of 1E-5 per year (rational for this value is described in Section 4.0) determine the 5% of the critically damped median spectral ground motion levels for the average of 5 and 10 Hz ($S_{5,10}$) and for the average of 1 and 2.5 Hz ($S_{1,2.5}$).
4. The median probabilistic hazard characterization should be deaggregated to determine the controlling earthquakes'[1] magnitudes and distances.

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[1] Given a reference probability (expressed as an annual probability of exceeding a ground motion level), the total seismic hazard can be de-aggregated to obtain contributions from different magnitude and distance events. The earthquakes which contribute most to this hazard are then called controlling earthquakes. This concept is schematically illustrated later.

After completing the PSHA and determining the controlling earthquakes, the following procedure should be used to determine the SSE.

5. With the controlling earthquakes determined as described above and using the procedures in Standard Review Plan (SRP) Section 2.5.2 (Ref.8), develop 5% of critical damping response spectral <u>shapes</u> for the actual or assumed rock conditions. The same controlling earthquakes are also used to derive vertical response spectral shapes.
6. Use S_{5-10} to scale the response spectrum shape corresponding to the controlling earthquake.
7. For nonrock sites, perform a site-specific soil amplification analysis considering uncertainties in site-specific geotechnical properties and parameters to determine response spectra at the free ground surface in the free-field for the actual site conditions.
8. Compare the smooth SSE spectrum or spectra used in design (e.g., 0.3g, broad-band spectra used in advanced light-water reactor designs) with the spectrum or spectra determined in Step 2 for rock sites or determined in Step 3 for nonrock sites to assess the adequacy of the SSE spectrum or spectra.

   When site-specific design response spectra are needed, to obtain an adequate design SSE based on the site-specific response spectrum or spectra, develop a smooth spectrum or spectra or use a standard broad band shape that envelopes the spectra of Step 6 or Step 7.

The concept of the methodology to estimate controlling earthquakes, outlined in steps 2 through 4, is illustrated in Figures 1,2, and 3. Figure 1 shows the total median seismic hazard curve in terms of 5 and 10 Hz spectral values. This figure also shows the ground motion levels at the reference probability, S_5 and S_{10}. The S_{5-10} is obtained by averaging S_5 and S_{10}. Figure 2 shows median seismic hazard curves for a set of magnitude and distance intervals defined in Table 1. Figure 3 shows graphically the contributions of magnitude and distance intervals to the ground motion level, S_{5-10}. In this figure, the major contributing earthquakes are nearby and of moderate size. Thus, in concept, this defines the notion of a controlling earthquake. Mathematically, the controlling earthquake are determined using the following equations:

$$M_c = \frac{\sum_m \sum_d m\overline{H_{md}}}{\sum_m \sum_d \overline{H_{md}}} \qquad Log(D_c) = \frac{\sum_m \sum_d Log(d)\overline{H_{md}}}{\sum_m \sum_d \overline{H_{md}}}$$

where M_c and D_c are magnitude and distance values of the controlling event. H_{md} is the average seismic hazard values of 5 and 10 Hz for each magnitude and distance interval (See Figure 2) estimated at ground motion levels for the reference probability.

Table 2 shows estimates of controlling earthquakes for several CEUS sites for the ground motion level corresponding to the reference probability of 1E-5/yr using LLNL median hazard results.

Once the controlling earthquake is determined, site specific spectral shape is derived using Ref.8. Figure 4 through 6 illustrate how the site specific spectral shape is used to develop SSE spectra or show adequacy of the previously selected SSE spectra (Steps 6 through 8). For engineering purposes, it is essential that the design ground motion response spectra be a broad-band smooth response spectra with adequate energy in the frequencies of interest. In the past, it was general practice to select standard broad-band spectra, such as the spectra in Regulatory Guide 1.60 (Ref.9), and scale them by a peak ground motion parameter (usually peak ground acceleration (PGA)), which is derived based on the size of the controlling earthquake. In the past licensing review these spectra were checked against site-specific spectral estimates to be sure that the SSE design spectra adequately enveloped the site-specific spectra. These past practices to define the SSE are still valid and, based on this consideration, the following three possible situations are depicted in Figures 4 through 6.

Figure 4 depicts a situation in which a site is to be used for a certified design with an established SSE (for instance, an Advanced Light Water Reactor with 0.3g PGA SSE). In this example, the certified design SSE spectrum compares favorably with the site-specific response spectra determined in Step 6 or 7.

Figure 5 depicts a situation in which a standard broad-band shape is selected and its amplitude is scaled so that the design SSE envelopes the site-specific spectra.

Figure 6 depicts a situation in which a specific smooth shape for the design SSE spectrum is developed to envelope the site-specific spectra. In this case, it is particularly important to be sure that the SSE contains adequate energy in the frequency range of engineering interest and is sufficiently broad-band.

In the regulatory guide the probabilistic approach has been chosen for several reasons. The probabilistic methods have been used in the licensing of several plants when issues of different interpretations have arisen by applying the deterministic procedures of Appendix A to Part 100. Two major probabilistic studies and databases exist for CEUS which facilitate uniform and reproducible implementation of the probabilistic methods. The probabilistic approach explicitly considers the likelihood of an event or recurrence period. The need to perform PSHAs is important in characterizing seismic sources in the CEUS due to relatively low seismicity and the inability to associate earthquakes with specific tectonic structures. However, experience in performing seismic hazard evaluations in active plate-margins regions in the western United States has also identified uncertainties associated with the characterization of seismic sources. Sources of uncertainties include fault geometry, rupture segmentation, rupture extent, seismic activity rate, ground motion, and earthquake occurrence modeling. As in the case for sites in the CEUS, alternative hypotheses and parameters must be considered to account for these uncertainties. Thus, the probabilistic approach is deemed as one acceptable approach in addressing the uncertainties in determining the SSE. However, as indicated in the rule and the regulatory guide, alternate approaches can be used to address uncertainties. Decision on how to best approach the issue of uncertainty depends on the knowledge of tectonics, seismic sources, historical records, and feasibility to do exploratory work.

4.0 REFERENCE PROBABILITY (RP)

One of the key parameters in implementing a probabilistic method is the reference probability (RP). In Reference 4 the RP of 1E-5/yr has been defined considering the design basis of certain recently licensed plants in CEUS. The RP is the annual probability level such that 50% of a set of currently operating plants has an annual median probability of exceeding the SSE below this level. The RP is determined for the annual probability of exceeding the average of the 5 and 10 Hz SSE response spectrum ordinates associated with 5% of critical damping.

The RP was calculated using the LLNL methodology and results, but is also considered applicable for the EPRI study. The selected plants represent relatively recent designs that used Regulatory Guide 1.60 or similar spectra as their design bases. The use of these plants should ensure an adequate level of conservatism in determining a SSE consistent with recent licensing decisions.

The following procedure was used to determine the RP and should be used in the future if general revisions to PSHA methods or data bases result in significant changes in hazard predictions for the selected plant sites.

1. Using LLNL methodology the median seismic hazard results were calculated for the selected sites for spectral responses at 5 and 10 Hz.

2. The composite annual probability of exceeding the plant SSE values for spectral responses at 5 and 10 Hz was calculated using median hazard estimates of Step 1. The composite annual probability is determined by:

   $$\text{Composite probability} = 1/2(a1) + 1/2(a2)$$

   where a1 and a2 represent median annual probabilities of exceeding SSE spectral ordinates at 5 and 10 Hz, respectively. The procedure is illustrated in Figure 7.

3. Figure 8 illustrates the distribution of median probabilities of exceeding the SSEs for selected 35 plants. The reference probability is simply the median probability of this distribution.

It should be noted that this RP is calibrated with the past design bases, it is not derived directly from any quantitative risk or safety goals. In fact, one of the reasons for using the median hazard curve in the regulatory guide approach is that the controlling earthquakes resulting from the de-aggregation of the median hazard curve are very similar to those used in the past licensing from the deterministic procedures. Table 3 shows a comparison of controlling earthquakes derived from the regulatory guide approach with those used in the past design. The regulatory guide recognizes that the final SSE at a higher RP may be more appropriate and acceptable for some sites considering the slope characteristics of the site hazard curves, the overall uncertainty in calculations (i.e., differences between mean and median hazard estimates), and the knowledge of the seismic sources that contribute to the hazard. The guide references a procedure, Ref.10, to determine an alternative reference probability on the risk-based considerations

A mean risk goal, such as seismically induced mean core damage frequency (cdf), is computed by a convolution of mean hazard with mean fragility, where fragility is the conditional probability of cdf given a particular hazard level. The relationship can be expressed as follows:

$$\text{mean goal} = \int \text{mean hazard} \bullet \text{mean fragility}$$

This relationship can be visualized from the schematic representation in Figure 9. The risk computations take into the account the entire hazard curve while the design basis is established based on the exceedance probability at one ground motion level. Clearly, the convolution of hazard curve 1 in Figure 9 with the fragility will produce higher mean cdf than the convolution of hazard curve 2. The slope of the hazard curve is an important parameter computing a mean risk goal.

For the CEUS sites, as shown in Figure 10, the median reference probability of 1E-5/yr corresponds to the mean probability of 1E-4. That is, the use of either mean of 1E-4 or median of 1E-5 will result in roughly the same ground motion level. Figure 11 shows situations where the risk implications may be quite different based on the slope of the overall hazard curve and the nature of uncertainty. Figure 11 shows a hypothetical CEUS and western US (WUS) situation. Since the mean and median are shown closer for the WUS site, use of the median reference probability from the CEUS site would imply that WUS plants should be designed to a more stringent risk criteria. In other words, if the risk-based considerations are to be applied, it may be more appropriate to use a different, and perhaps mean-based, reference probability. For the hypothetical situation shown in Figure 11, while the use of mean RP of 1E-4 would result into the same ground motion level, S_{CEUS}, as using the median RP of 1E-5 for the CEUS site, there will be a substantial difference in the ground motion levels S_{W1} and S_{W2} resulting from the use of median RP of 1E-5 versus the use of mean RP of 1E-4.

ACKNOWLEDGMENT

Many people have participated in the revision of rule and preparation of the regulatory guides described in this paper. Don Bernreuter, Auguste Boissonnade, and Jean Savy of LLNL were primary NRC contractors conducting technical studies. An expert panel consisting of Dr. Robert Budnitz, Prof. C. Allin Cornell, Dr. Kevin Coppersmith, Mr. James Devine, Dr. Walter Hays, Dr. Robert Kennedy, and Dr. Paul Pomeroy provided critical reviews. Many of the concepts emerged during the interactions with the panel. There were also intensive interactions with industry groups. The seismic ad-hoc group established by the Nuclear Energy Institute provided many comments and conducted technical studies which were also used in the development of the regulation and guidance. The NRC staff members, Mr. Goutam Bagchi, Dr. Phyllis Sobel, and Dr. Abou-Bakr Ibrahim were also integral members of the team which was charged to revise the rule. Finally, the comments provided by many individuals and institutions during the two public review periods help clarify many issues and have shaped the final rule.

DISCLAIMER

The views expressed in this paper are those of the authors and should not be construed to reflect the official U.S.NRC position.

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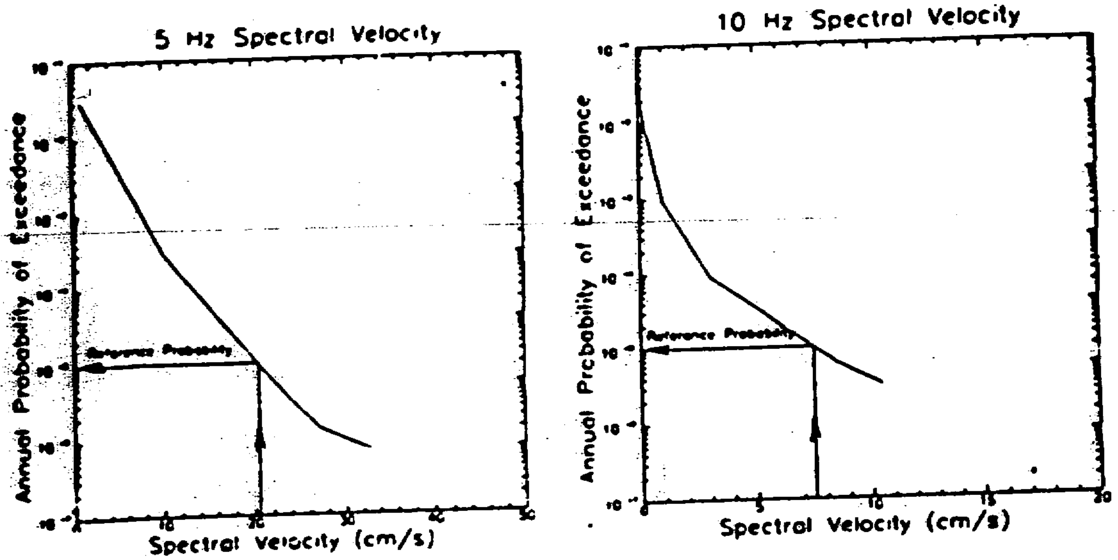

Fig.1 Total median seismic hazard for a site

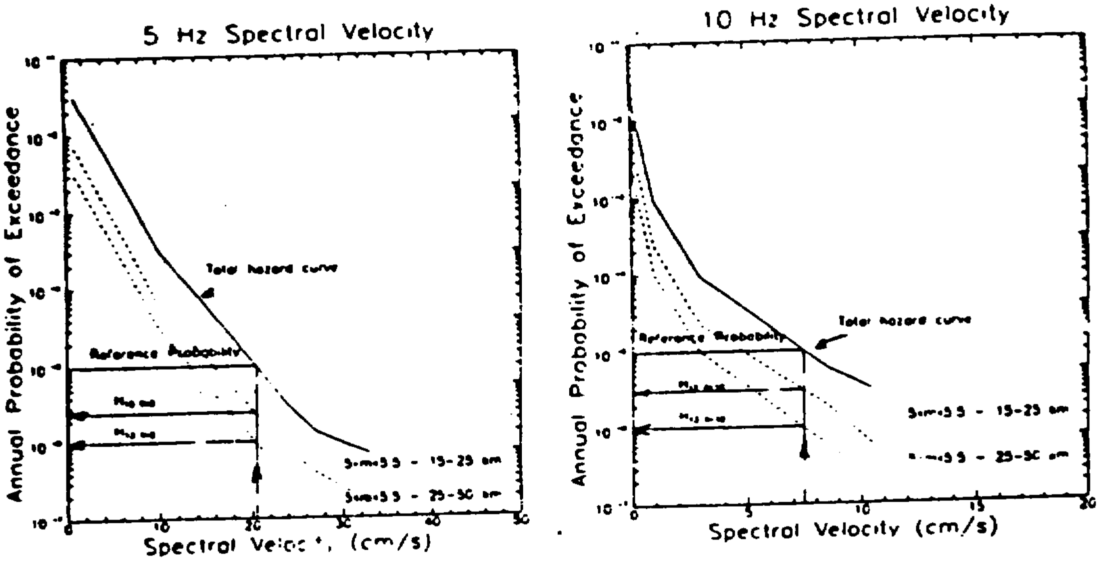

Fig.2 Deaggregated median seismic hazard for a site

Table 1
Contribution of Magnitude-Distance Intervals to Total Hazard

Distance Range of Bin (km)	Magnitude Range of Bin				
	5 - 5.5	5.5 - 6	6 - 6.5	6.5 - 7	> 7
0-15	0.417	0.097	0.000	0.000	0.000
15-25	0.220	0.079	0.000	0.000	0.000
25-50	0.080	0.042	0.000	0.000	0.000
50-100	0.004	0.014	0.001	0.000	0.000
100-200	0.000	0.008	0.031	0.000	0.000
200-300	0.000	0.001	0.004	0.000	0.000
300	0.000	0.000	0.000	0.000	0.002

Table 2
Estimates of Controlling Earthquakes

Site No.	Controlling Earthquake (Case 1)	
	Magnitude	Distance (km)
1	5.7	23
2	5.8	18
3	5.8	18
4	5.5	19
5	5.7	19
6	5.6	18
7	5.5	20
8	5.5	21

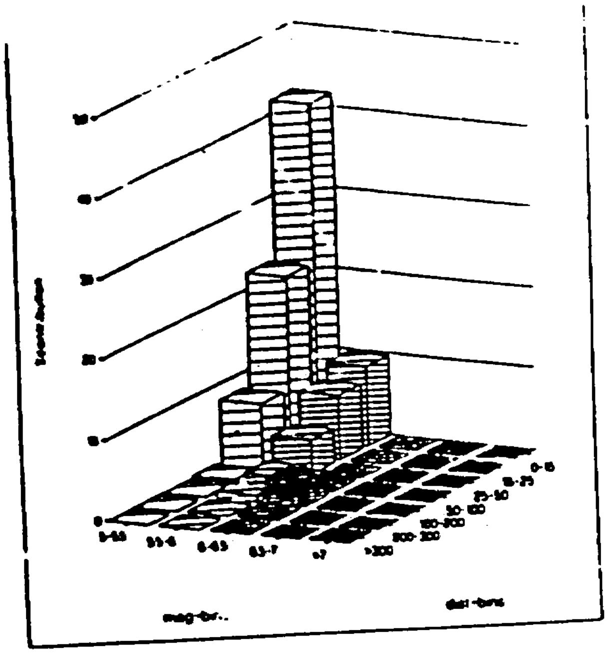

Fig 3 Contribution of magnitude-distance intervals for the average of 5 and 10 Hz spectral accelerations

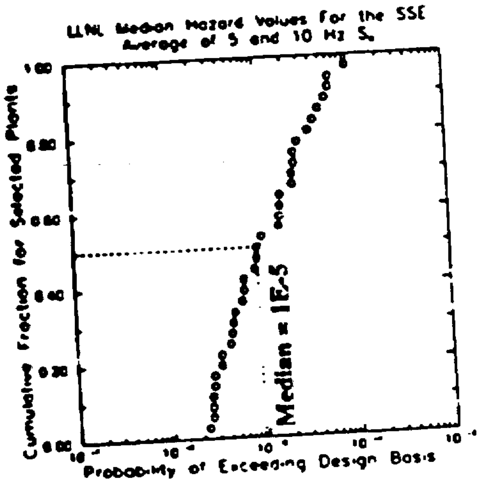

Fig.8 Distribution of the probability of exceeding the SSE at 5-10 Hz

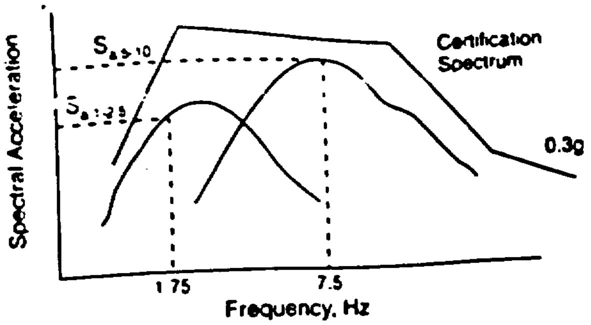

Figure 4 Use of SSE Spectrum of a Certified Design

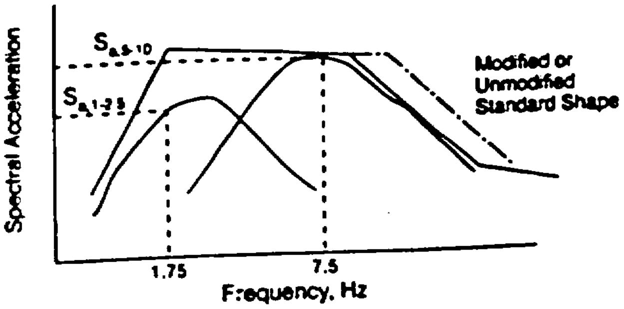

Figure 5 Use of a Standard Shape for SSE

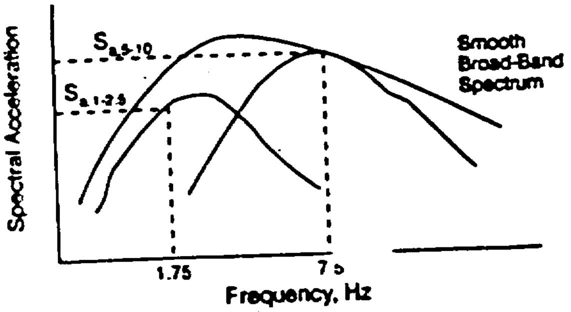

Figure 6 Development of a Site-Specific SSE Spectrum

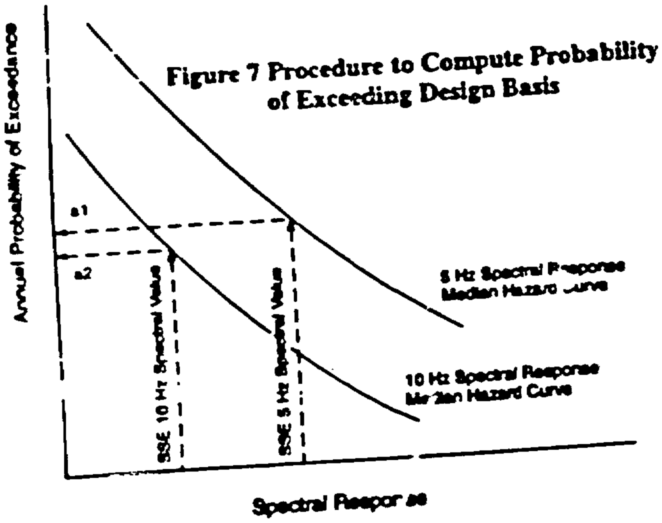

Figure 7 Procedure to Compute Probability of Exceeding Design Basis

Table 3
Comparison between Controlling Earthquakes and Past Seismic Design Criteria

Site No	Controlling Earthquakes		Past Seismic Design	
	Magnitude	Distance (km)	Magnitude	Distance (km)
1	5.4	18	5.0	15
2	5.6 7.2	24 275	5.8 7	15 250
3	5.5	14	5.3	15
4	5.6	14	5.3	15
5	5.7	14	5.7	15
6	5.5	16	5.3	15
7	5.3 7.3	18 340	4.8 7.3	15 370
8	5.7	14	6	15
9	5.6	14	5.8	15

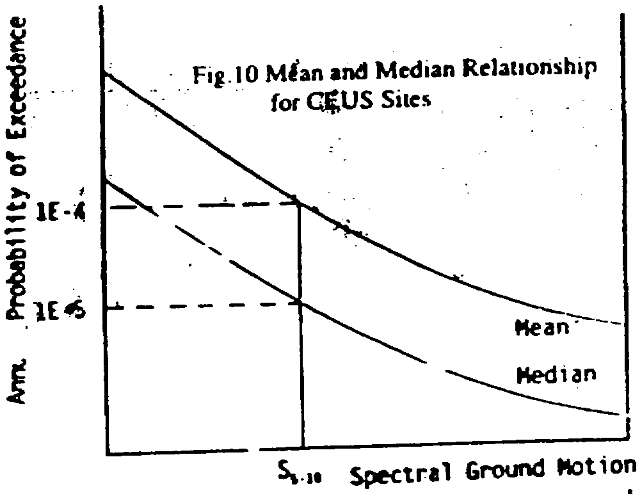

Fig.10 Mean and Median Relationship for CEUS Sites

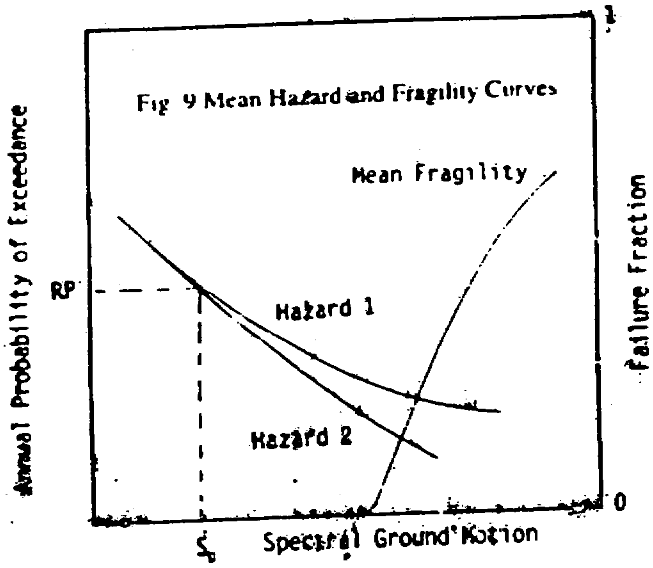

Fig 9 Mean Hazard and Fragility Curves

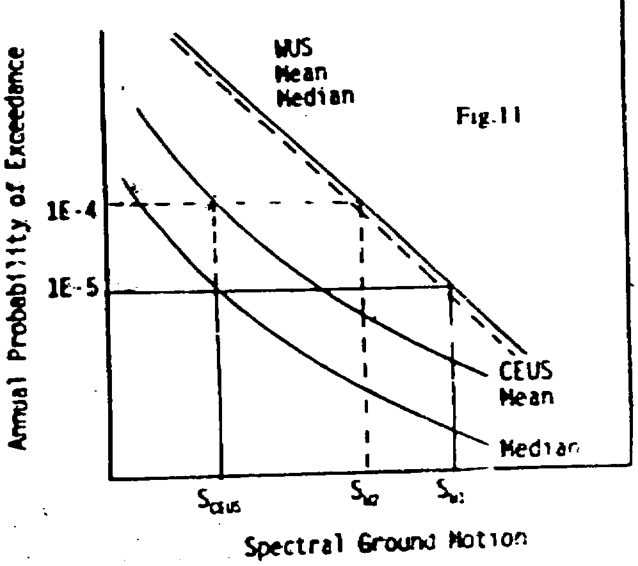

Fig.11