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Determination of controlling earthquakes from probabilistic seismic hazard analysis for nuclear reactor sites

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ABSTRACT: Recently, the U.S. Nuclear Regulatory Commission published, for public comments, a revision to 10 CFR Part 100. The proposed regulation acknowledges that uncertainties are inherent in estimates of the Safe Shutdown Earthquake Ground Motion (SSE) and requires that these uncertainties be addressed through an appropriate analysis. One element of this evaluation is the assessment of the controlling earthquake through the probabilistic seismic hazard analysis (PSHA) and its use in determining the SSE. This paper reviews the basis for the various key choices in characterizing the controlling earthquake.

1 INTRODUCTION

During the past 10 years, probabilistic procedures developed specifically for nuclear plant seismic hazard assessments in the central and eastern United States have provided a structured approach, when performed together with site-specific investigations, for determining the SSE.

PSHA methodologies are powerful tools for incorporating uncertainties associated with identifying and characterizing seismic sources and defining ground shaking levels consistent with given safety criteria (for example, a $1\text{x}10^{-5}$ annual probability of exceeding the seismic design loading). However, because these methods provide a composite analysis of all possible earthquakes that may occur, they do not provide the familiar link between seismic design loading requirements and engineering design practice. Seismic design generally requires the type of events (expressed in terms of magnitude and distance) and the type of seismic source within which the event occurs.

An acceptable procedure, in addition to the purely probabilistic approach, is to use PSHA to determine one or several hazard-consistent scenarios (controlling earthquakes) from the probabilistic analysis. These events are then used to develop site-specific spectral shapes and design ground motion.

In this paper, we describe the concepts of the controlling earthquake and the key choices that have to be made in assessing its characterization.

2 CONCEPT AND METHODOLOGY TO ESTIMATE CONTROLLING EARTHQUAKES

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.

Although approaches for characterizing these earthquakes were introduced in the literature (Ishikawa and Kameda 1992; McGuire and Sheldock 1981) for single and multiple sources, they did not address the case of PSHA treating uncertainties resulting from the consideration of multiple seismic source interpretations and alternative ground motion attenuation models. This is the case with present methodologies used to assess seismic hazards in the central and eastern United States (Sobel 1993; EPRI 1989).

The draft Regulatory Guide (DG-1032 1995) gives the mathematical details for determining the controlling earthquakes. The concept of the methodology to estimate controlling earthquakes is illustrated by the following example. Figure 1 shows the total median seismic hazard curve in terms of 5 and 10 Hz spectral velocities. 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 total hazard for the average of 5 and 10 Hz. In this example, the major contributing earthquakes are nearby and of moderate sizes. Thus, in concept, this defines the notion of a controlling earthquake. Mathematically, the controlling earthquakes 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 the distance and magnitude values of the controlling event. H_{md} is the average seismic hazard values of 5 and 10 Hz for each magnitude and distance intervals (See Figure 2) estimated at ground motion levels for the reference probability (See Figure 1).

There are three critical parameters which will affect the determination of the controlling earthquakes: (1) ground motion parameter, (2) selection of reference probability, and (3) selection of parameters for the deaggregation process. In the following, studies related to these parameters are discussed.

2.1 Ground motion parameter

The most representative ground motion parameter for determining the controlling earthquakes is selected as the average of the 5 and 10 Hz response spectral accelerations. This was based on judgement derived from analysis of a number of typical nuclear power plant structures and systems to earthquake ground motion. In addition, the average of the 1 and 2.5 Hz spectral accelerations was selected to determine controlling earthquakes which may be located at large distances (> 100 km). The purpose of this calculation is to identify a distant but larger event which may control the low frequency content of site response spectra.

2.2 Reference probability

The NRC staff has defined the reference probability of exceeding the seismic design basis by considering the experience data base of some 70 operating plants in the central and eastern United States (DG-1032 1995). The specific reference probability is the annual probability level such that 50% of a set of currently operating plants has an annual median probability of exceeding the SSE ground motion level (average of 5 and 10 Hz design basis spectrum). Although the reference probability is dependent on probabilistic hazard studies, this value is similar for both the 1993 LLNL (DG-1032 1995) and EPRI (McCann et al. 1994) seismic hazard studies. Figure 4 illustrates the distribution of median probabilities of exceeding the SSE's based on the LLNL seismic hazards results.

Sensitivity analyses were conducted to analyze the impact of using different seismic hazard analyses on the controlling earthquakes. Figure 5 shows the differences in magnitude and distance values using the 1989 LLNL, 1993 LLNL and EPRI studies for 14 sites in the central and eastern United States. Note that the reference probabilities have changed with the different hazard analyses. Little variation is observed in magnitudes and only a relatively small variation in distances.

Although it is recognized that different reference probability values for the same hazard analysis methodology may produce different ground motion levels, it is expected that the characteristics of the controlling earthquakes would be relatively insensitive to the change. Figure 6 shows the variations in magnitude for an order of difference in the reference probability values using the LLNL study for eight central and eastern United States sites.

2.3 Selection of parameters for the de aggregation process

Sensitivity analyses were conducted to assess the impact of the choice of the set of discrete magnitude distance pairs on the controlling earthquakes. Table 2 summarizes the results of this analysis. Although small changes are observed in the evaluation of magnitudes, the choice of discrete sets of magnitude-distance pairs mostly impacts the distance estimates.

3 INTERPRETATION OF CONTROLLING EARTHQUAKES

Applying the methodology for determining controlling earthquakes for existing nuclear power plant sites in the central and eastern United States shows that the results are consistent with past design earthquakes. Table 3 lists a representative sample comparing controlling earthquakes and past design earthquakes. For most sites, the controlling earthquakes are at distances less than 20 km and of magnitudes less than 6.0.

Sensitivity analyses were also conducted to assess the impact of seismicity around a site. A hypothetical site is located between a fault with high seismicity and a seismic zone with low seismicity. The closer the site is to the high seismicity area, the larger the magnitude of the controlling earthquake. Conversely, the closer the site is to the low seismicity area, the smaller the magnitude of the controlling earthquake.

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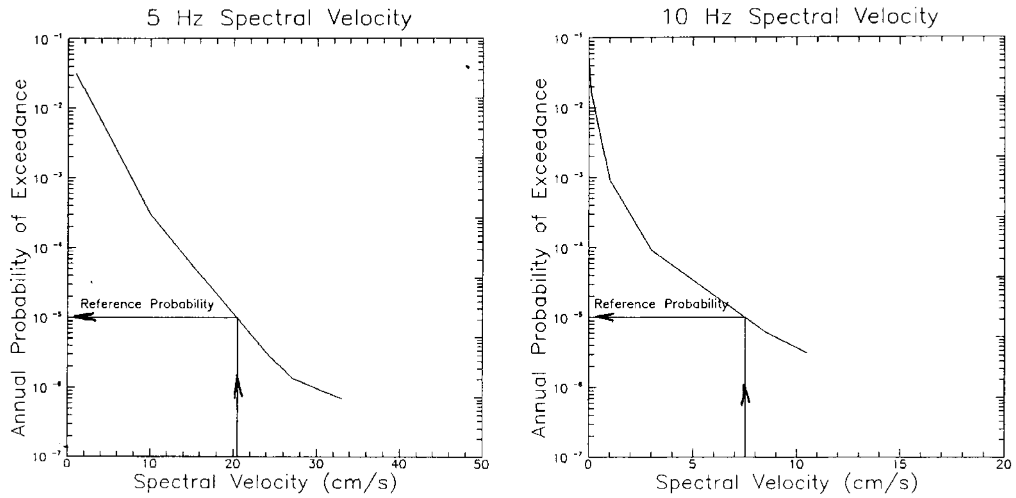

Fig. 1 Total median seismic hazard for a site

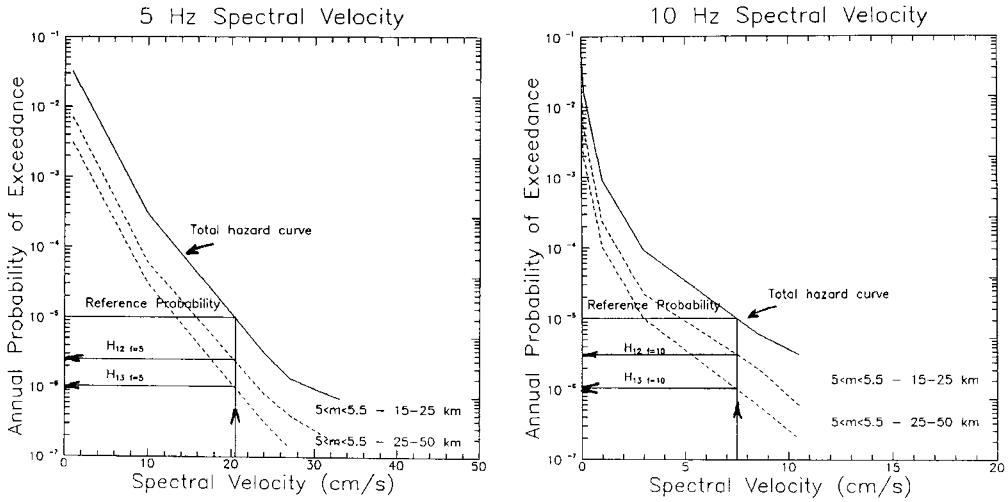

Fig. 2 De-aggregated median seismic hazard for a site

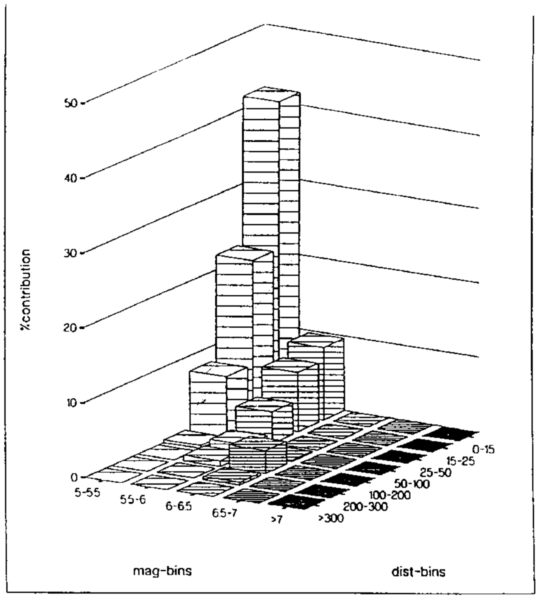

Fig. 3 Contribution of magnitude-distance intervals for the average of 5 and 10 Hz spectral accelerations

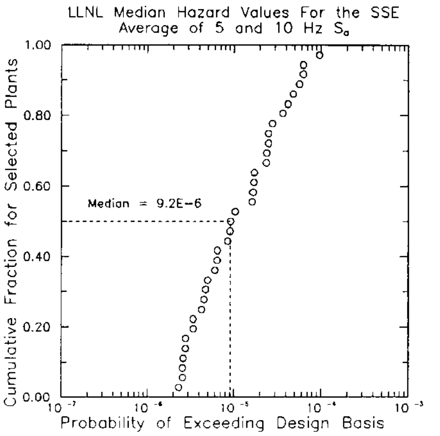

Fig. 4 Distribution of the probability of exceeding the SSE at 5-10 Hz

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)		Controlling Earthquake (Case 2)	
	Magnitude	Distance (km)	Magnitude	Distance (km)
1	5.7	23	5.7	19
2	5.8	18	5.7	13
3	5.8	18	5.8	14
4	5.5	19	5.5	15
5	5.7	19	5.7	14
6	5.6	18	5.6	14
7	5.5	20	5.5	16
8	5.5	21	5.5	18

Case 1: Magnitude: 5-5.5, 5.5-6.0, 6.0-6.5, >6.5
Distance : 0-25, 25-50, 50-100, >100

Case 2: Magnitude: 5-5.5, 5.5-6.0, 6.0-6.5, 6.5-7.0, >7.0
Distance : 0-15, 15-25, 25-50, 50-100, 100-200, 200-300, >300

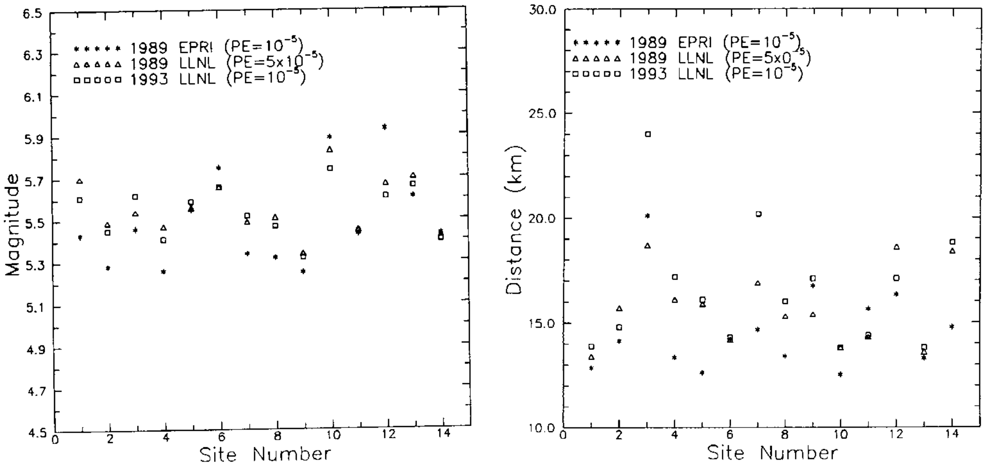

Fig. 5 Characteristics of the controlling earthquakes, magnitude (a) and distance (b) using different methodologies

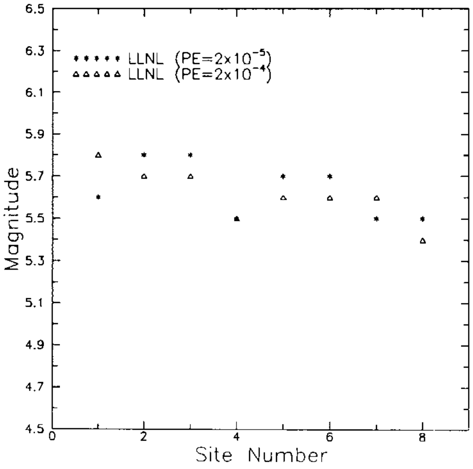

Fig. 6 Controlling earthquake magnitudes for several reference probabilities

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