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GUIDANCE ON DESIGN GROUND MOTION FOR CRITICAL FACILITIES

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SUMMARY

In 1996, the U.S. Nuclear Regulatory Commission (NRC) amended its regulations to update the criteria used in decisions regarding nuclear power plant siting, including geologic, seismic and earthquake engineering considerations for future applications. As a follow-on to the revised siting regulations, it is necessary to develop state-of-the-art recommendations on the design ground motions commensurate with seismological knowledge and engineering needs. The paper will review the revised seismic and geologic siting criteria, and the scope of the work associated with the development of design ground motion, indicate the direction the recommendations are taking, present preliminary results, and discuss some implications.

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 (Code of Federal Regulations, Title 10, Energy, Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants," to 10 CFR 100, "Reactor Siting Criteria."). Although it has been a relatively successful licensing tool for over two decades, significant difficulties have been encountered in applying it. For example, while there have been substantial advances in the geosciences, it has been difficult or impossible to accommodate these changes or to modify the criteria because of the inherent inflexibility of a regulation. 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. In this deterministic approach, an applicant develops a single set of earthquake sources, develops for each source a postulated earthquake to be used as the source of ground motion that can affect the site, locates the postulated earthquake according to prescribed rules, and then calculates ground motions at the site. Typically, peak ground acceleration (PGA) is estimated and standard broad-band spectra, such as the spectra in Regulatory Guide 1.60[NRC 1973] shown in Fig.1, are scaled to derive the design basis Safe Shutdown Earthquake (SSE) ground motion.

REVISION OF SEISMIC AND GEOLOGIC SITING CRITERIA

Revised Siting Rule and Procedure

In 1996, NRC published a revised siting rule for new plant applications [NRC 1997a] to overcome some of the difficulties encountered in implementing Appendix A, to incorporate lessons learned from the past experiences, to facilitate application of new knowledge, and to create a more stable licensing process. This regulation explicitly states that uncertainties are inherent in such estimates of Safe Shutdown Earthquake Ground Motion (SSE), and that these uncertainties must be addressed through an appropriate analysis, such as a probabilistic seismic hazard analysis or suitable sensitivity analyses. In 1997, NRC published Regulatory Guide 1. 165[(NRC 1997b] to provide general guidance on procedures acceptable to the NRC staff for: 1. conducting geological, seismological, and geophysical investigations; 2. identifying and characterizing seismic sources; 3. conducting probabilistic seismic hazard analyses; and 4. determining the SSE for satisfying the requirements of the new siting rule.

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The following paragraph provides an abbreviated discussion of the step-wise procedure outlined in the guide to determine the SSE at a site. Refer to the guide for precise definitions and a detailed example illustrating the procedure.

Step 1 - Regional and site geological, seismological, and geophysical investigations should be performed.

Step 2 - For central and eastern US (CEUS) sites (sites east of the Rocky Mountains), the Lawrence Livermore National Laboratory (LLNL) [NRC 1994] or the Electrical Power Research Institute (EPRI) [EPRI 1989] Probabilistic Seismic Hazard Analysis (PSHA) should be performed using original or updated sources. The ground motion estimates should be made for real or hypothetical rock conditions in the free-field.

Step 3 - Using the reference probability (RP) of 1E-5 per year (rational for this value is described later) 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 ($S_{1-2.5}$).

Step 4 - The median probabilistic hazard characterization should be deaggregated to determine the controlling earthquakes magnitudes (**M**) and distances[1](**D**).

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

Step5 - With the controlling earthquakes determined as described above and using the procedures in [NRC 1997c], develop 5% of critical damping response spectral shapes for the actual or assumed rock conditions.

Step 6 - Use S_{5-10} to scale the response spectrum shape corresponding to the controlling earthquake.

Step 7 - For nonrock sites, perform a site-specific soil amplification analysis considering uncertainties to determine response spectra at the free ground surface in the free-field for the actual site conditions.

Step 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 6 for rock sites or determined in Step 7 for nonrock sites to assess the adequacy of the SSE spectrum or spectra.

The concept of the methodology to estimate controlling earthquakes, outlined in steps 2 through 4, is illustrated in Figures 2,3, and 4. Figure 2 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 3 shows median seismic hazard curves for a set of magnitude and distance intervals. Figure 4 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. The mean magnitude and mean distance of the distribution in Figure 4 define the controlling earthquake for S_{5-10}. Table 1 shows comparison of controlling earthquakes derived using the Regulatory Guide 1.165 procedure with the earthquakes used in past seismic design for some CEUS sites.

Once the controlling earthquake is determined, site specific spectral shape is derived using [NRC 1997b]. Figure 5 through 7 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**.** Figure 5 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 6 depicts a situation in which a standard broad-band shape(e.g., Regulatory Guide 1.60) is selected and its amplitude is scaled so that the design SSE envelopes the site-specific spectra. Figure 7 depicts a situation in which a specific smooth shape for the design SSE spectrum is developed to

[1] *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.*

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.

Reference Probability

One of the key parameters in implementing a probabilistic method is the RP or target exceedance probability. In [NRC 1997b] the RP of IE-5/yr has been defined considering the design basis of 35 recently licensed plants in CEUS that used Regulatory Guide 1.60 or similar spectra as their design bases. 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 use of this RP should ensure an adequate level of conservatism in determining an SSE consistent with recent licensing decisions. 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.

REVISION TO DESIGN RESPONSE SPECTRA

As a follow-on to the revised siting regulations, it is necessary to develop state-of-the-art recommendations on the design ground motions commensurate with seismological knowledge and engineering needs. The current design spectra in [NRC 1973] were based on limited, principally western United States earthquake strong-motion records, available at that time. Since 1996, the NRC has funded a project to develop up-to-date seismic design spectra for the US.

The overall objectives of this project are (1) to update the standardized design spectra used in the evaluation of nuclear facilities to accommodate the effects of magnitude, site condition, distance, and tectonic environment, (2) assemble a database of strong motion records appropriate for use in design analyses, (3) recommend procedures and requirements for the scaling of ground motion records to be consistent with design spectra, (4) develop recommendations for conducting site response analyses to produce soil motions consistent with rock outcrop hazard results (hazard consistency), and (5) develop recommendations on how to derive seismic design spectra that provide risk consistency (uniform conservatism) across structural frequency. Procedures developed in this project are being currently applied to two sites as trial application and they may change based on the outcome of this trial application.

Development of Revised Spectral Shapes

The revised spectral shapes accommodate continuous **M** and **D** scaling as well as potential differences in western United States (WUS) and CEUS earthquake source processes. They are normalized by PGA, since it is the spectral ordinate with lowest variability, and are provided for both soft and hard rock site conditions occurring in either WUS or CEUS.

The intended use of the revised motions is to provide more realistic spectral shapes for applications of the Regulatory Guide 1.165 procedure to develop an overall design spectrum. In this procedure, spectral shapes are scaled to the rock outcrop uniform hazard spectra (UHS) or risk consistent spectra (RCS, discussed later) at high (_ 10 Hz) and at low (_ 1 Hz) frequencies. For both frequency ranges, shapes are used which reflect the dominant contributions in both **M** and **D** to the UHS. The advantage of this approach, combined with realistic spectral shapes, is that the scaled shapes will represent seismic events that dominate the hazard for different structural frequency ranges as well as distance ranges. The use of rock outcrop control motions avoids the ambiguities in going from soil surface motions to foundation levels and provides for the direct development of site specific motions which accommodate variability in dynamic material properties.

Time History Database For Analysis

An important aspect of this project is the development of a time history database for analyses. The database is parsed into **M** and **D** bins which were selected to preserve significant differences in spectral composition and time domain characteristics (e.g. duration). The bins are also appropriate for potential high and low frequency controlling earthquakes in both the WUS and CEUS. The database is to provide appropriate records for spectral matching as well as for scaling. Since each bin contains records reflecting ranges in **M** and **D**, guidelines are given for within bin **M** and **D** adjustments for either constant or narrow band scaling.

For applications to the WUS, the bins are populated largely with recorded motions. Sparse bins have been supplemented with scaled empirical records (from adjoining bins) as well as a few direct finite-fault simulations. For the CEUS, since few recordings exist, the bins are not populated, however, they can be populated with CEUS/WUS scaled records, i.e., a scaling procedure for converting WUS records to CEUS records could be applied. While not as desirable as recorded motions, these time histories are considered suitable for analyses.

Site Specific Soil Motions

The most desirable form of site specific motions are suites of hazard curves appropriate for the soil surface, embedment depth, as well as any other site conditions upon which critical structures are founded. The site specific hazard curves, from which the required sets of UHS may be obtained, should also accommodate uncertainty in site specific dynamic material properties as well as local and regional seismicity and attenuation characteristics. This ideal situation of exact hazard consistency would then permit direct assessment of risk consistency for structures, systems, and components since both the hazard curve and its local (near the desire hazard level) slope are required. The only way to accomplish this is to generate site specific attenuation relations. While this approach has been used on several occasions (for a single rock/soil column), it is not a particularly straightforward task involving many assumption and several limitations. A rock PSHA can be performed with regional, not site-specific data, and so can be completed prior to site-specific soil parameters being collected. Also, if multiple distinct soil columns exist at a plant site, or if some critical structures are founded on soil and some on rock, the same rock PSHA should be used for all. Finally, if new soil data are collected, the effects on design spectra can be determined quickly, without redoing the PSHA. For all of these reasons, it is recommended to perform the PSHA for appropriate rock (rock like) conditions, then modify the rock UHS to reflect the effects of local soils.

There are several approaches to estimate soil UHS given rock outcrop UHS. In the project, these methods are compared to directly computed soil UHS using site specific attenuation relations. Applying these methods at two hazard levels one can then approximate the slope of the soil hazard curve. Also developed are approximate methods to compute the soil hazard curve given rock UHS and suites of convolutional analyses.

Development of Risk-Consistent Spectra

One of the objectives in developing seismic design spectra is to achieve approximate uniformity of seismic risk for structures, equipment, and components designed to those spectra, across a range of seismic environments, annual probabilities, and structural frequencies. That is, the procedures should not result in relatively high seismic risk for certain conditions, and relatively low seismic risk for others.

The procedures for developing risk-consistent spectra are determined by examining nine existing nuclear plant sites in the central and eastern US, and two hypothetical sites in the western US (California and Washington). Existing seismic hazard curves are used to convolve seismic hazard with component fragility curves to calculate probabilities of failure for a range of structural frequencies. The characteristics of seismic hazard span the range of amplitudes and slopes that can be expected in the US.

A simple modification to the UHS must be made to achieve risk-consistency across structural frequencies. This modification accounts for the slope of the hazard curve; the UHS is increased where the slope is shallow, and is decreased where the slope is steep, so that approximately uniform risks result from choosing a UHS with a target annual probability of accedence. Figure 9 shows a comparison between design spectrum, UHS, and RCS for an existing nuclear power plant site in CEUS.

Development of Design Spectra

In the procedure under consideration, the spectral shape for controlling earthquakes for 1 Hz and 10 Hz spectral responses (and for responses at additional frequencies, if needed) will be scaled by the RCS ground motion level. The question of enveloping as shown in Figures 5 through 7, is still an open issue. Instead of a single envelope spectrum, individual spectra from each of the controlling earthquakes may be used in the analysis. The use of individual spectra will avoid unrealistic ground motion that may result from the broadened shape. Furthermore, increased broadening of the shapes can lead to potentially unconservative soil motions due to nonlinearity. Both, Regulatory Guides 1.60 and 1.165 are expected to be revised after the procedure is finalized, and have gone through wide peer review process involving public comments and resolution process. Full details are under development and will be published in a NRC report; however, details of some of the aspects discussed above can be found in (McGuire 1998)

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DISCLAIMER

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

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Table 1
Comparison between Controlling Earthquakesand Past Seismic Design Criteria

Site No.	Controlling Earthquakes		Past Seismic Design	
	Magnitude	Distance(km)	Magnitude	Distance(km)
1	5.4	18	5.0	1.5
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