U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REGULATORY RESEARCH

October 2006
Division 1

DRAFT REGULATORY GUIDE

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DRAFT REGULATORY GUIDE DG-1146

A PERFORMANCE-BASED APPROACH TO DEFINE THE SITE-SPECIFIC EARTHQUAKE GROUND MOTION

A. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) proposes this draft regulatory guide as an alternative to Regulatory Guide 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion," (Ref. 1), for use in satisfying the requirements set forth in Section 100.23,"Geologic and Seismic Siting Criteria," of Title 10, Part 100, of the *Code of Federal Regulations* (10 CFR Part 100), "Reactor Site Criteria," as well as Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities." The NRC staff has recognized the need to provide alternative guidance for incorporating recent developments in ground motion estimation models; updated models for earthquake sources; methods for determining site response; and new methods for defining a site-specific, performance-based safe shutdown earthquake ground motion (SSE).

In 10 CFR 100.23, paragraph (c), "Geological, Seismological, and Engineering Characteristics," and paragraph (d), "Geologic and Seismic Siting Factors," require that the geological, seismological, and engineering characteristics of a site and its environs be investigated in sufficient scope and detail to permit an adequate evaluation of the proposed site, provide sufficient information to support evaluations performed to arrive at estimates of the SSE, and permit adequate engineering solutions to actual or potential geologic and seismic effects at the proposed site. Data on the vibratory ground motion; tectonic and nontechtonic surface deformation; earthquake recurrence rates, fault geometry and slip rates, site foundation material; seismically induced floods and water waves; and other siting factors and design conditions should be obtained by reviewing pertinent literature and carrying out field investigations.

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10 CFR 100.23, paragraph (d)(1), "Determination of the Safe Shutdown Earthquake Ground Motion," requires that uncertainty inherent in estimates of the SSE be addressed through an appropriate analysis, such as a probabilistic seismic hazard analysis (PSHA).

In Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, General Design Criterion (GDC) 2, "Design Bases for Protection Against Natural Phenomena," requires, in part, that nuclear power plant structures, systems, and components (SSCs) important to safety must be designed to withstand the effects of natural phenomena (such as earthquakes) without loss of capability to perform their safety functions. Such SSCs must also be designed to accommodate the effects of, and be compatible with, the environmental conditions associated with normal operation and postulated accidents.

Appendix S to 10 CFR Part 50 specifies, in part, requirements for implementing GDC 2 with respect to earthquakes. Paragraph IV(a)(1)(i), of Appendix S to 10 CFR Part 50, requires that the SSE must be characterized by free-field ground motion response spectra at the free ground surface. In view of the limited data available on vibratory ground motions of strong earthquakes, it will usually be appropriate that the design response spectra be smoothed spectra. In addition, the horizontal motions in the free field at the foundation level of the structures consistent with the SSE must be an appropriate response spectrum with a peak ground acceleration of at least 0.1g.

The two-step licensing practice, which required applicants to acquire a construction permit (CP), and then apply for an operating license (OL) during construction, has been modified to allow for an alternative procedure. The requirements and procedures applicable to the NRC's issuance of early site permits (ESPs) and combined licenses (COLs) for nuclear power facilities are set forth in Subparts A and C of 10 CFR Part 52, respectively.

This regulatory guide has been developed to provide general guidance on methods acceptable to the NRC staff for (1) conducting geological, geophysical, seismological, and geotechnical investigations; (2) identifying and characterizing seismic sources; (3) conducting a PSHA; (4) determining seismic wave transmission (soil amplification) characteristics of soil and rock sites; and (5) determining a site-specific, performance-based earthquake ground motion, satisfying the requirements of paragraphs (c), (d)(1), and (d)(2) of 10 CFR 100.23, and leading to the establishment of an SSE to satisfy the requirements of Appendix S to 10 CFR Part 50. NUREG-0800, "Standard Review Plan," Section 3.7.1, describes the determination of the SSE, and a conceptual overview is provided in Regulatory Position 5.4 of this guide.

This regulatory guide contains several appendices that address the objectives stated above. Appendix A contains a list of definitions. Appendix B contains a list of abbreviations and acronyms. Appendix C discusses a procedure to characterize site geology, seismology, and geophysics. Appendix D describes the procedure to determine the controlling earthquakes. Appendix E describes the procedure for determining seismic wave transmission (soil amplification) characteristics of soil and rock sites. Appendix F provides criteria for developing and evaluating modified ground motions used for soil response analyses.

The NRC issues regulatory guides to describe to the public methods that the staff considers acceptable for use in implementing specific parts of the agency's regulations, to explain techniques that the staff uses in evaluating specific problems or postulated accidents, and to provide guidance to applicants. Regulatory guides are not substitutes for regulations, and compliance with regulatory guides is not required. The NRC issues regulatory guides in draft form to solicit public comment and involve the public in developing the agency's regulatory positions. Draft regulatory guides have not received complete staff review and, therefore, they do not represent official NRC staff positions.

This regulatory guide may address information collections that are covered by the requirements of 10 CFR Part 50, 10 CFR Part 52, and 10 CFR Part 100, which the Office of Management and Budget (OMB) approved under OMB control numbers 3150-0011, 3150-0151, and 3150-0093, respectively. The NRC may neither conduct nor sponsor, and a person is not required to respond to, an information collection request or requirement unless the requesting document displays a currently valid OMB control number.

B. DISCUSSION

Background

Regulatory Guide 1.165 (Ref. 1) provides general guidance on procedures acceptable to the NRC staff to satisfy the requirements of 10 CFR 100.23. However, the NRC staff has recognized the need to provide alternative guidance for incorporating recent developments in ground motion estimation models; updated models for earthquake sources; methods for determining site response; and new methods for defining a site-specific, performance-based SSE. Therefore, the NRC staff is proposing this draft regulatory guide as an alternative to Regulatory Guide 1.165 (Ref. 1) to satisfy, in part, the requirements of 10 CFR 100.23 and Appendix S to 10 CFR Part 50.

The general process to determine a site-specific, performance-based earthquake ground motion includes the following:

(1) site- and region-specific geological, seismological, geophysical, and geotechnical investigations
(2) a probabilistic seismic hazard analysis (PSHA)
(3) a site response analysis to incorporate the effects of local geology and topography
(4) and the selection of appropriate performance goals and methodology

Geological, seismological, and geophysical investigations are performed to develop an up-to-date, site-specific, earth science database that supports site characterization and a PSHA. The results of these investigations will also be used to assess whether new data and their interpretation are consistent with the information used in accepted probabilistic seismic hazard studies.

The PSHA is conducted with up-to-date interpretations of earthquake sources, earthquake recurrence, and strong ground motion estimation. The site seismic hazard characteristics are quantified by the seismic hazard curves from a PSHA and the uniform hazard response spectra (UHRS) that cover a broad range of natural frequencies. The hazard curves are developed in part by identifying and characterizing each seismic source in terms of maximum magnitude, magnitude recurrence relationship, and source geometry. The rock-based ground motion at a site resulting from the combined effect of all sources can then be determined through the use of attenuation relationships.

Seismic wave transmission (site amplification) procedures are necessary to obtain appropriate UHRS at the free-field ground surface if the shear wave velocity of the surficial material is less than the generic hard rock conditions appropriate for the rock-based attenuation relationships used in the PSHA. A database of earthquake time histories on rock for both the central and eastern United States (CEUS) and the western United States (WUS) has been developed to determine the dynamic site response for the soil or rock site conditions.[1]

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[1] The CEUS and WUS Time History databases provided in NUREG/CR-6728 (Ref. 2) are being updated and will be available in the Summer of 2007.

A performance-based approach is described in Chapters 1 and 2 of ASCE/SEI Standard 43-05 (Ref. 3), instead of the reference probability approach described in Appendix B to Regulatory Guide 1.165 (Ref. 1).[2] The performance-based approach employs Target Performance Goal (P_F), Probability Ratio (R_P), and Hazard Exceedance Probability (H_D) criteria[3] to ensure that nuclear power plants can withstand the effects of earthquakes with desired performance, the desired performance being expressed as the target value of 1E-05 for the mean annual probability of exceedance of onset of significant inelastic deformation (FOSID). Setting the performance goal to be equivalent to the FOSID of SSCs is conservative, since the seismic demand resulting in the onset of significant inelastic deformation is less than that for failure of the SSCs.

One of the objectives in developing the performance-based SSE is to achieve approximate consistent performance for SSCs, across a range of seismic environments, annual probabilities, and structural frequencies. The intent is to develop a site-specific SSE that achieves the P_F and ensures that the performance of the SSCs related to safety and environmental protection is acceptable.

Basis for Regulatory Positions

Site- and Region-Specific Investigations to Characterize Site Geology, Seismology and Geophysics

The primary objective of geological, seismological, and geophysical investigations is to develop an up-to-date, site-specific earth science database that supports site characterization and a PSHA. The results of these investigations will also be used to assess whether new data and their interpretation are consistent with the information used in accepted probabilistic seismic hazard studies. If the new data, such as new seismic sources and new ground motion attenuation relationships, are consistent with the existing earth science database, updating or modification of the hazard analysis is not required. It will be necessary to update seismic sources and ground motion attenuation relationships for sites where there is significant new information resulting from the site investigations.

Features Discovered During Construction

It should be demonstrated that deformation features discovered during construction, particularly faults, do not have the potential to compromise the safety of the plant. Applying the combined licensing procedure to a site could result in the award of a license prior to the start of construction. During the construction of nuclear power plants licensed in the past, previously unknown faults were often discovered in site excavations. Before issuance of the OL, it was necessary to demonstrate that faults in the excavation posed no hazard to the facility. Under the combined license procedure, these kinds of features should be mapped and assessed as to their rupture and ground motion generating potential while the excavations' walls and bases are exposed, and the NRC staff should be notified when excavations are open for inspection.

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2 The reference probability is computed as the median probability obtained from the distribution of median probabilities of exceeding the SSE at 29 sites in the CEUS. The sites selected were intended to represent relatively recent designs that used the Regulatory Guide 1.60 (Ref. 4), design response spectrum, or similar spectrum, as their design bases. The use of the reference probability was to ensure an adequate level of conservatism in determining the SSE consistent with recent licensing decisions.

3 The P_F, R_P, and H_D criteria corresponding to Seismic Design Category (SDC) 5 in Reference 3 (which are equivalent to nuclear power plant requirements) are used.

Probabilistic Seismic Hazard Analysis Methods

A PSHA has been identified in 10 CFR 100.23 as a means to address the uncertainties in the determination of the SSE. Furthermore, the rule recognizes that the nature of uncertainty and the appropriate approach to account for uncertainties depend on the tectonic setting of the site and on properly characterizing input parameters to the PSHA, such as the seismic source characteristics, the recurrence of earthquakes within a seismic source, the maximum magnitude of earthquakes within a seismic source, and engineering estimation of earthquake ground motion through attenuation relationships.

Every site is unique; therefore, requirements for analyses and investigations vary. It is not possible to provide procedures for addressing all situations. In cases that are not specifically addressed in this regulatory guide, prudent and sound engineering judgment should be exercised.

Probabilistic procedures were developed specifically for nuclear power plant seismic hazard assessments in the CEUS, also referred to as the Stable Continent Region (SCR). Experience has been gained by applying this methodology at nuclear facility sites, both reactor and non-reactor sites, throughout the United States. The experience with these applications also served as the basis for the guidelines for conducting a PSHA in Reference 5. These procedures provide a structured approach for decision making with respect to the SSE when performed with site-specific investigations. A PSHA provides a framework to address the uncertainties associated with the identification and characterization of seismic sources by incorporating multiple interpretations of seismological parameters. A PSHA also provides a means for evaluation of the likelihood of SSE occurrence during the design lifetime of a given facility, given the recurrence interval and recurrence pattern of earthquakes in pertinent seismic sources. Within the framework of a probabilistic analysis, uncertainties in the characterization of seismic sources and ground motions are identified and incorporated in the procedure at each step of the process for estimating the SSE. The role of geological, seismological, and geophysical investigations is to develop geoscience information about the site for use in the detailed design analysis of the facility, as well as to ensure that the seismic hazard analysis is based on up-to-date information.

Experience in performing seismic hazard evaluations in active plate-margin regions in the WUS (for example, the San Gregorio-Hosgri fault zone and the Cascadia Subduction Zone) has also identified uncertainties associated with the characterization of seismic sources (Refs. 6–8). Sources of uncertainty include fault geometry, rupture segmentation, rupture extent, seismic-activity rate, ground motion, and earthquake occurrence modeling. As is the case for sites in the CEUS, alternative hypotheses and parameters must be considered to account for these uncertainties.

Uncertainties associated with the identification and characterization of seismic sources in tectonic environments in both the CEUS and the WUS should be evaluated. The same basic approach can be applied to determine the SSE.

Central and Eastern United States

The CEUS is considered to be that part of the United States east of the Rocky Mountain front, or east of Longitude 105° West (Refs. 9, 10) A PSHA in the CEUS must account for credible alternative seismic source models through the use of a decision tree with appropriate weighting factors that are based on the most up to date information and relative confidence in alternative characterizations for each seismic source. Seismic sources identified and characterized by the Lawrence Livermore National Laboratory (LLNL) (Refs 9–11) and the Electric Power Research Institute (EPRI) (Refs. 12, 13) were used for studies in the CEUS in the past. These databases may still represent the latest information available for some seismic sources. However, if more up to date information is available, it should be incorporated if significant.

In the CEUS, characterization of seismic sources is more problematic than in active plate-margin regions because there is generally no clear association between seismicity and known tectonic structures or near-surface geology. In general, the observed geologic structures are a result of response to tectonic forces that may have little or no correlation with current tectonic forces. Therefore, it is important to account for this uncertainty by the use of multiple alternative seismotectonic models.

The identification of seismic sources and reasonable alternatives in the CEUS considers hypotheses currently advocated for the occurrence of earthquakes in the CEUS (e.g., the reactivation of favorably oriented zones of weakness or the local amplification and release of stresses concentrated around a geologic structure). In tectonically active areas of the CEUS, such as the New Madrid Seismic Zone, where geological, seismological, and geophysical evidence suggest the nature of the sources that generate the earthquakes, it may be more appropriate to characterize those seismic sources by using procedures similar to those normally applied in the WUS.

Western United States

The WUS is considered to be that part of the United States that lies west of the Rocky Mountain front, or west of approximately 105° West Longitude. In some regions of the WUS, significant research into seismic sources is ongoing and the results of this research should be evaluated and addressed.

The active plate-margin regions include, for example, coastal California, Oregon, Washington, and Alaska. For the active plate-margin regions, where earthquakes can often be correlated with known faults that have experienced repeated movements at or near the ground surface during the Quaternary, tectonic structures should be assessed for their earthquake and surface deformation potential. In these regions, at least three types of sources may exist:

(1) faults that are known to be at or near the surface
(2) buried (blind) sources that may often be manifested as folds at the earth's surface
(3) subduction zone sources, such as those in the Pacific Northwest and Alaska

The nature of surface faults can be evaluated by conventional surface and near-surface investigation techniques to assess orientation, geometry, sense of displacements, length of rupture, Quaternary history, etc. Possibilities of multiple ruptures should be considered, as appropriate.

Buried (blind) faults are often associated with surficial deformation such as folding, uplift, or subsidence. The surface expression of blind faulting can be detected by mapping the uplifted or down-dropped geomorphological features or stratigraphy, survey leveling, and geodetic methods. The nature of the structure at depth can often be evaluated by deep core borings and geophysical techniques.

Continental U.S. subduction zones are located in the Pacific Northwest and Alaska. Seismic sources associated with subduction zones are sources within the overriding plate, on the interface between the subducting and overriding lithospheric plates, and in the interior of the downgoing oceanic slab. The characterization of subduction zone seismic sources should consider the three-dimensional geometry of the subducting plate, rupture segmentation of subduction zones, geometry of historical ruptures, constraints on the up-dip and down-dip extent of rupture, and comparisons with other subducting plates worldwide.

The Basin and Range region of the WUS, and to a lesser extent the Pacific Northwest and the central United States, exhibit temporal clustering of earthquakes. Temporal clustering is best exemplified by the rupture histories within the Wasatch fault zone in Utah, where several large, late Holocene coseismic faulting events occurred at relatively close intervals (for hundreds to thousands of years) that were preceded by long periods of quiescence that lasted thousands to tens of thousands of years. Temporal clustering should be considered in these regions, or wherever paleoseismic evidence indicates that it has occurred.

Lower-Bound Magnitude Cutoff

Current seismic hazard analysis methods generally utilize a lower-bound body wave magnitude cut-off value for earthquakes to be included in the PSHA. This lower-bound magnitude cut-off level is a conservatively defined value based on research studies whose objective was to estimate the damage potential of smaller earthquakes. Reference 14 establishes an appropriate distribution of low-magnitude earthquakes in the seismic hazard analysis through the use of the cumulative absolute velocity (CAV) model, in place of a lower-bound magnitude cutoff.

Several ground motion measures such as peak ground acceleration, Arias intensity, root mean square acceleration, and CAV were evaluated to determine the single ground motion measure that is best correlated with the threshold of potential damage. The CAV was determined to be the best parameter correlating damage with the Modified Mercalli Intensity Scale, and a CAV value of 0.16 g-sec was found to be a conservative characterization of the threshold between damaging and non-damaging earthquake motions for buildings of good design and construction. An empirical model for estimating CAV in terms of magnitude, peak ground acceleration (PGA), and duration is needed because the PSHA calculation does not use time histories directly.

Spectral Frequency Range Considered in the Probabilistic Seismic Hazard Analyses

The frequency range considered in the PSHA should extend from a low frequency that can be reliably obtained from the current strong-motion data set from the WUS, principally California, to a high-frequency limit that permits the ratio of spectral acceleration to PGA to reach nearly 1 for hard rock site conditions. For the CEUS this high-frequency limit is approximately 100 Hz. For soft rock conditions, the ratio of spectral acceleration to PGA will reach 1 at about 40–50 Hz. To obtain a smooth plot of spectral response across the frequency range of interest, the hazard assessment should be conducted at a minimum of 30 frequencies, approximately equally spaced on a logarithmic frequency axis between 100 and 0.1 Hz.

Deaggregation of Mean Hazard

High- and low-frequency controlling earthquakes are developed for the ground motion levels corresponding to mean annual probabilities of 1 E-04, 1 E-05, and 1 E-06, by deaggregating the PSHA in terms of earthquake magnitudes and distances. Multiple ground motion levels are used to obtain a more complete range of earthquake characteristics (i.e., mean magnitudes and distances) that contribute to the high-frequency (5 and 10 Hz) and low-frequency (1 and 2.5 Hz) hazard, than could be obtained from a single ground motion level (e.g., 1 E-05/yr).

Choice of Epsilon in Probabilistic Seismic Hazard Analyses

Epsilon, the number of standard deviations included in defining the distribution of ground motions for each magnitude and distance scenario, can have a significant impact on the results of the PSHA. Care should be taken in choosing a value for epsilon large enough such that natural aleatory variability in ground motions is adequately addressed. A recent study (Ref. 15) found no technical basis for truncating the ground motion distribution at a specified number of standard deviations (epsilons) below that implied by the strength of the geologic materials. Even though very large ground motions may have a low probability of occurrence, when the hazard is calculated for low annual frequencies of exceedance, low probability events need to be considered.

Site Response Analysis

For rock or soil sites where the free-field ground surface shear wave velocity is less than the generic hard rock conditions used in the PSHA, seismic wave transmission (site amplification) procedures should be used to obtain appropriate UHRS at the free-field ground surface. Earthquake time histories are used to determine the dynamic site response for the soil or rock site conditions. Reference 2 contains a database of recorded time histories on rock for both the CEUS and WUS. The database is divided into magnitude and distance bins, with each bin having a minimum of 15, three-component (two horizontal and one vertical) sets.

Performance-Based Method

A performance-based approach is described in Chapters 1 and 2 of ASCE/SEI Standard 43-05 (Standard) (Ref. 3). The Standard was developed by a number of contributors considered to be experienced in the design of nuclear facilities, and reviewed by a number of outside agencies and personnel. It is a national consensus standard by the American Society of Civil Engineers (ASCE).

The Standard was developed to provide performance-based criteria for the seismic design of safety-related SSCs for use in nuclear facilities. The Standard covers a broad range of facilities that process, store, or handle radioactive materials. The goal of the Standard is to present seismic design criteria using a graded approach commensurate with the relative importance to safety and safeguards, which will ensure that nuclear facilities can withstand the effects of earthquakes with desired performance, expressed as probabilistic target performance goals and hazard exceedance probabilities. The performance-based approach used for this regulatory guide is based on the premise that the seismic demand and structural capacity evaluation criteria laid out by the NRC's Standard Review Plan (SRP) (NUREG-0800) are aimed at having sufficient conservatism to reasonably achieve both of the following:

(1) less than about a 1% probability of unacceptable performance for the site-specific response spectrum ground motion

(2) less than about a 10% probability of unacceptable performance for a ground motion equal to 150% of the site-specific response spectrum ground motion.

The Standard, for the most demanding seismic design category (SDC 5), recommends using a P_F = 1 E-05 for the FOSID, R_P = 10, and H_D = 1 E-04 for the minimum structural damage state, which is described as essentially elastic behavior. Specifically, essentially elastic behavior means that localized inelasticity might occur at stress concentration points, but the overall seismic response will be essentially elastic. SDC 5 criteria are nearly identical to the NRC SRP (NUREG-0800), regulatory guides, and professional design codes and standards referenced therein. Also, setting the performance goal of 1 E-05/yr to be equivalent to the FOSID of SSCs is conservative, since the seismic demand resulting in the onset of significant inelastic deformation is less than that for failure of the SSC.

Thus, the performance-based approach combines a conservative characterization of ground motion hazard with equipment/structure performance (fragility characteristics) to establish risk-consistent SSEs, rather than only hazard-consistent ground shaking, as occurs using the hazard reference probability approach in Appendix B to Regulatory Guide 1.165 (Ref. 1). The performance target (the mean annual probability of SSCs reaching the limit state of inelastic response) results from the integration of the hazard function and the fragility function which is modeled by two parameters, the mean capacity of SSCs using the acceptance criteria provided in NUREG 0800, and the variability β.[4]

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[4] After the design of SSCs is completed by the performance-based method described above, the resulting SSCs should be demonstrated to have HCLPF capacity 1.67 times the SSE response spectra for evolutionary and new reactors. HCLPF represents the seismic capacity corresponding to a 1-percent mean probability of failure and the β represents the composite uncertainty.

The UHRS at the free-field ground surface is modified by a design factor to obtain the performance-based site-specific response spectrum. The design factor achieves a relatively consistent annual probability of plant component failure across the range of plant locations and structural frequencies. It does this by determining a ground motion slope ratio (amplitude ratio), accounting for the slope of the seismic hazard curve, which changes with structural frequency and site location. The design factor ensures that the site-specific response spectrum is equal to or greater than the mean 1 E-04 UHRS.

The flow chart in Figure 1 depicts the procedures described in this regulatory guide.

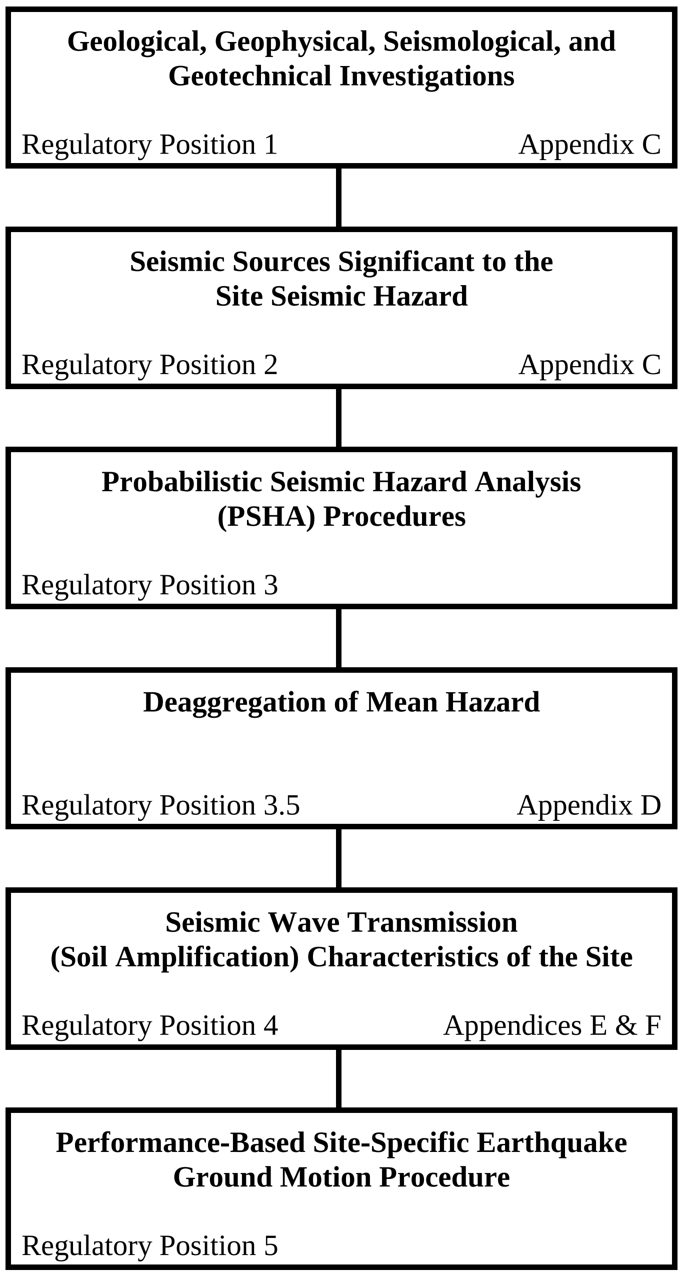


Figure 1. Flow Diagram

C. REGULATORY POSITION

1. Geological, Geophysical, Seismological, and Geotechnical Investigations

1.1 <u>Comprehensive Site Area and Region Investigations</u>

Comprehensive geological, seismological, geophysical, and geotechnical engineering investigations of the site area and region should be performed. For existing nuclear power plant sites where additional units are planned, the geosciences technical information originally used to validate those sites may need to be updated. Depending on how much new or additional information has become available since the initial investigations and analyses were performed and the complexity of the site and regional geology and seismology, additional data may be required. This technical information should be used, along with all other available information, to plan and determine the scope of additional investigations. The investigations described in this regulatory guide are performed primarily to gather information needed to confirm the suitability of the site and to gather data pertinent to the safe design and construction of the nuclear power plant. Appropriate geological, seismological, and geophysical investigations are described in Appendix C to this regulatory guide. Geotechnical investigations are described in Regulatory Guide 1.132 (Ref. 16). Another important purpose for the site-specific investigations is to determine whether there are any new data or interpretations that are not adequately incorporated into the existing PSHA databases. Appendix C also describes a method for assessing the impact of new information, obtained during the site-specific investigations on the databases used for the PSHA.

These investigations should be performed at four levels, with the degree of detail based on (a) distance from the site, (b) the nature of the Quaternary tectonic regime, (c) the geological complexity of the site and region, (d) the existence of potential seismic sources, and (e) the potential for surface deformations, etc. A more detailed discussion of the areas and levels of investigations and the bases for them are presented in Appendix C to this regulatory guide. General guidelines for the levels of investigation are characterized as follows.

1.1.1 *Within a Radius of 320 Kilometers (200 mi) of the Site (Site Region)*

Conduct regional geological and seismological investigations to identify seismic sources (seismogenic and capable tectonic sources). These investigations should include literature reviews, the study of maps and remote sensing data, and, if necessary, ground-truth reconnaissances.

1.1.2 *Within a Radius of 40 Kilometers (25 mi) of the Site (Site Vicinity)*

Geological, seismological, and geophysical investigations should be carried out in greater detail than the regional investigations, to identify and characterize the seismic and surface deformation potential of any capable tectonic sources and the seismic potential of seismogenic sources, or to demonstrate that such structures are not present. Sites with capable tectonic or seismogenic sources within a radius of 40 kilometers (km) (25 mi) may require more extensive geological and seismological investigations and analyses [similar in detail to investigations and analysis usually preferred within an 8 km (5 mi) radius].

1.1.3 *Within a Radius of 8 Kilometers (5 mi) of the Site (Site Area)*

Detailed geological, seismological, geophysical, and geotechnical engineering investigations should be conducted to evaluate the potential for tectonic deformation at or near the ground surface and to assess the transmission characteristics of soils and rocks in the site vicinity.

1.1.4 *Within a Radius of Approximately 1 Kilometer (0.6 mi) of the Site (Site Location)*

Very detailed geological, geophysical, and geotechnical engineering investigations should be conducted to assess specific soil and rock characteristics, as described in Reference 16.

1.2 Expanding the Areas of Investigation

The areas of investigation may be expanded beyond those specified above in regions that include seismogenic tectonic sources, relatively high seismicity, or complex geology, or in regions that have experienced a large, geologically recent earthquake identified in historical records or by paleoseismic data.

1.3 Features Discovered During Construction

It should be demonstrated that deformation features discovered during construction, particularly faults, do not have the potential to compromise the safety of the plant. The newly identified features should be mapped and assessed as to their rupture and ground motion generating potential while the excavations' walls and bases are exposed. A commitment should be made, in documents (Safety Analysis Reports) supporting the license application, to geologically map all excavations and to notify the NRC staff when excavations are open for inspection.

1.4 Justifying Assumptions and Conclusions

Data sufficient to clearly justify all assumptions and conclusions should be presented. Because engineering solutions cannot always be satisfactorily demonstrated for the effects of permanent ground displacement, it is prudent to avoid a site that has a potential for surface or near-surface deformation. Such sites normally will require extensive additional investigations.

1.5 Characterize Lithologic, Stratigraphic, Hydrologic, and Structural Geologic Conditions

For the site and for the area surrounding the site, the lithologic, stratigraphic, hydrologic, and structural geologic conditions should be characterized. The investigations should include the measurement of the static and dynamic engineering properties of the materials underlying the site as well as an evaluation of the physical evidence concerning the behavior during prior earthquakes of the surficial materials and the substrata underlying the site. The properties needed to assess the behavior of the underlying material during earthquakes should be measured. These include the potential for liquefaction and the characteristics of the underlying material in transmitting earthquake ground motions to the foundations of the plant (such as seismic wave velocities, density, water content, porosity, elastic moduli, and strength).

2. Seismic Sources Significant to the Site Seismic Hazard

2.1 Evaluation on New Seismic Sources

For sites in the CEUS, existing databases may be used to identify seismic sources to perform PSHA. Previously unidentified seismic sources that were not included in these databases should be appropriately characterized and sensitivity analyses performed to assess their significance to the seismic hazard estimate. The results of investigation discussed in Regulatory Position 1 should be used, in accordance with Appendix C to this regulatory guide, to determine whether the seismic sources and their characterization should be updated. The guidance in Regulatory Positions 2.2 and 2.3 (below) and the methods in Appendix C to this regulatory guide may be used if additional seismic sources are to be developed as a result of investigations.

2.2 Use of Alternative Seismic Sources

When existing methods and databases are not used or are not applicable, the guidance in Regulatory Position 2.3 should be used for identification and characterization of seismic sources. The uncertainties in the characterization of seismic sources should be addressed. "Seismic sources" is a general term referring to both seismogenic sources and capable tectonic sources. The main distinction between these two types of seismic sources is that a seismogenic source would not cause surface displacement, but a capable tectonic source causes surface or near-surface displacement.

Identification and characterization of seismic sources should be based on regional and site geological and geophysical data, historical and instrumental seismicity data, the regional stress field, and geological evidence of prehistoric earthquakes. Investigations to identify seismic sources are described in Appendix C to this regulatory guide. The bases for the identification of seismic sources should be described. A general list of characteristics to be evaluated for seismic sources is presented in Appendix C.

2.3 Characterizing Seismic Potential

As part of the seismic source characterization, the seismic potential for each source should be evaluated. Typically, characterization of the seismic potential consists of four equally important elements:

(1) selection of a model for the spatial distribution of earthquakes in a source

(2) selection of a model for the temporal distribution of earthquakes in a source

(3) selection of a model for the relative frequency of earthquakes of various magnitudes, including an estimate for the largest earthquake that could occur in the source under the current tectonic regime

(4) a complete description of the uncertainty

For example, truncated exponential and characteristic earthquake models are often used for the distribution of magnitudes. A stationary Poisson process is used to model the spatial and temporal occurrences of earthquakes in a source. For a general discussion of evaluating the earthquake potential and characterizing the uncertainty, refer to NUREG/CR- 6372 (Ref. 5).

2.3.1 *Characterizing Seismic Potential When Alternative Methods and Databases Are Used*

For sites in the CEUS where previous source databases are not used, it is necessary to evaluate the seismic potential for each source. The seismic sources and data accepted by the NRC in past licensing decisions may be used, along with the data gathered from the investigations carried out as described in Regulatory Position 1.

Generally, the seismic sources for the CEUS are area sources because there is uncertainty about the underlying causes of earthquakes. This uncertainty is caused by a lack of active surface faulting, a low rate of seismic activity, or a short historical record. The assessment of earthquake recurrence for CEUS area sources commonly relies heavily on catalogs of historic earthquakes. Because these catalogs are incomplete and cover a relatively short period of time, the earthquake recurrence rate may not be estimated reliably. Considerable care must be taken to correct for incompleteness and to model the uncertainty in the rate of earthquake recurrence. To completely characterize the seismic potential for a source, it is also necessary to estimate the largest earthquake magnitude that a seismic source is capable of generating under the current tectonic regime. This estimated magnitude defines the upper bound of the earthquake recurrence relationship.

Primary methods for assessing maximum earthquakes for area sources usually include a consideration of the historical seismicity record, the pattern and rate of seismic activity, the Quaternary geologic record (2 million years and younger), characteristics of the source, the current stress regime (and how it aligns with known tectonic structures), paleoseismic data, and analogs to sources in other regions considered tectonically similar to the CEUS. Because of the shortness of the historical catalog and low rate of seismic activity, considerable judgment is needed. It is important to characterize the large uncertainties in the assessment of the earthquake potential (Refs. 5 and 12).

2.3.2 *Characterizing Seismic Potential for Western United States Sites*

For sites located within the WUS, earthquakes can often be associated with known tectonic structures with a high degree of certainty. For faults, the earthquake potential is related to the characteristics of the estimated future rupture, such as the total rupture area, the length, or the amount of fault displacement. Empirical relations can be used to estimate the earthquake potential from fault behavior data and also to estimate the amount of displacement that might be expected for a given magnitude. It is prudent to use several different rupture length or area-versus-magnitude relations to obtain an estimate of the earthquake magnitude. When such correlations are used, the earthquake potential is often evaluated as the mean of the distribution. The difficult issue is the evaluation of the appropriate rupture dimension to be used. This is a judgmental process based on geological data for the fault in question and the behavior of other regional fault systems of the same type.

In addition to maximum magnitude, the other elements of the recurrence model are generally obtained using catalogs of seismicity, fault slip rate, and other data. All the sources of uncertainty must be appropriately modeled.

2.3.3 *Characterizing Seismic Potential for Sites Near Subduction Zones*

For sites near subduction zones, such as in the Pacific Northwest and Alaska, the maximum magnitude must be assessed for subduction zone seismic sources. Worldwide observations indicate that the largest known earthquakes are associated with the plate interface, although intraslab earthquakes may also have large magnitudes. The assessment of plate interface earthquakes can be based on estimates of the expected dimensions of rupture or analogies to other subduction zones worldwide.

3. Probabilistic Seismic Hazard Analysis Procedures

A PSHA should be performed to allow for the use of multiple source models to estimate the likelihood of earthquake ground motions occurring at a site and to systematically take into account uncertainties that exist in various parameters (such as seismic sources, maximum earthquakes, and ground motion attenuation). Alternative hypotheses are considered in a quantitative fashion in a PSHA. They can be used to evaluate the sensitivity of the hazard to the uncertainties in the significant parameters and to identify the relative contribution of each seismic source to the hazard.

The following steps describe a procedure acceptable to the NRC staff for performing a PSHA.

3.1 Perform Regional and Site Investigations

Perform regional and site geological, seismological, and geophysical investigations in accordance with Regulatory Position 1 and Appendix C to this regulatory guide.

3.2 Evaluation of New Information

For CEUS sites, perform an evaluation of seismic sources, in accordance with Appendix C to this regulatory guide, to determine whether they are consistent with the site-specific data gathered in Regulatory Position 3.1 or if they require updating. The PSHA should be updated if the new information indicates that the current version of the seismic source model underestimates the hazard or if new attenuation relationships are available. In most cases, limited-scope sensitivity studies are sufficient to demonstrate that the existing database in the PSHA envelops the findings from site-specific investigations. Any significant update should follow the guidance of NUREG/CR- 6372 (Ref. 5).

3.3 Conduct a Probabilistic Seismic Hazard Analysis

Perform a site-specific PSHA with up-to-date interpretations of earthquake sources, earthquake recurrence, and strong ground motion estimation using original or updated sources as determined in Regulatory Positions 3.1 and 3.2. Characterize epistemic uncertainties in a complete and defensible fashion. CAV filtering can be used in place of a lower-bound magnitude cutoff of 5.0 (Ref. 14). For the CEUS, the understanding of single- and double-corner ground-motion models is evolving, and the PSHA should fully document the appropriateness of using either or both of these models. Aleatory variability of the ground motion as expressed in the choice of epsilon used in the PSHA should be considered carefully and described. The ground motion estimates should be made in the free field to develop the seismic hazard information base discussed in Appendix D to this regulatory guide.

3.4 Hazard Assessment

Conduct the hazard assessment at a minimum of 30 frequencies, approximately equally spaced on a logarithmic frequency axis between 100 and 0.1Hz. Report fractile hazard curves at the following fractile levels (p) for each ground motion parameter: 0.05, 0.16, 0.50, 0.84, and 0.95, as well as the mean. Report the fractile hazard curves in tabular as well as graphical format. Determine the mean UHRS for annual exceedance frequencies of 1 E-04, 1 E-05, and 1 E-06.

3.5 Deaggregate the Mean Probabilistic Hazard Characterization

Deaggregate the mean probabilistic hazard characterization at ground motion levels corresponding to the annual frequencies of 1 E-04, 1 E-05, and 1 E-06 in accordance with Appendix D to this regulatory guide to determine the controlling earthquakes (i.e., magnitudes and distances) and document the hazard information base as discussed in Appendix D.

4. Seismic Wave Transmission Characteristics of the Site

The hazard curves from the PSHA are defined for generic surficial hard rock conditions [i.e., rocks with a shear wave velocity (V_s) about 2.8 km/sec (9200 ft/sec)]. Because the surficial and subsurface shear wave velocities at nuclear power plant sites are generally less than 2.8 km/sec (9200 ft/sec), the following procedure should be used to define the UHRS at the free-field ground surface. Additional discussion pertaining to this regulatory position is provided in Appendix E to this regulatory guide.

For both soil and rock sites, the subsurface model should extend to sufficient depth to reach the generic hard rock conditions as defined in the attenuation relationships used in the PSHA.

4.1 Site and Laboratory Investigations and Testing

Perform site and laboratory investigations and testing to obtain data defining the static and dynamic engineering properties of the site-specific soil and rock materials, and their spatial distribution. Methods acceptable to the NRC staff are described in Regulatory Guide 1.132 (Ref. 16), Regulatory Guide 1.138 (Ref. 17), and Subsection C.2.2.2 of Appendix C to this regulatory guide. Sufficient site property data should be developed to adequately estimate the mean and variability of the properties in the site response calculations. When soil models are deduced from laboratory studies, critically peer review the sampling and testing programs to ensure that the generated soil dynamic nonlinear properties are appropriate to properly characterize site response.

4.2 Dynamic Site Response

The high- and low-frequency controlling earthquakes are derived in accordance with Regulatory Position 3.5 and Appendix D to this regulatory guide. Determine the dynamic site response by developing appropriate ground motion or earthquake time histories for each of the controlling earthquakes. Reference 2 contains a database of recorded time histories on rock for both the CEUS and WUS. The database is divided into magnitude and distance bins, with each bin having a minimum of 15, three-component (two horizontal and one vertical) sets. Appendix F to this regulatory guide provides criteria acceptable to the NRC staff for developing and evaluating modified ground motions used for soil response and structural analyses. The time histories are scaled to match the response spectrum for the corresponding controlling earthquake.

Often vertically propagating shear waves are the dominant contributor to free-field ground motions at a site. In these cases, a one-dimensional equivalent-linear analysis or nonlinear analysis that assumes vertical propagation of shear waves may be appropriate. However, site characteristics (such as a dipping bedrock surface, topographic effects or other impedance boundaries), regional characteristics (such as certain topographic effects), and source characteristics (such as nearby dipping seismic sources) may require that analyses are also able to account for inclined waves.

Use a Monte Carlo or equivalent procedure to accommodate the variability in soil depth, shear wave velocities, layer thicknesses, and strain-dependent dynamic nonlinear material properties at the site. Perform a sufficient number of convolution analyses using scaled earthquake time histories to adequately capture the effect of the site subsurface variability and the uncertainty in the soil properties. Generally, at least 60 convolution analyses should be performed to define the mean and the standard deviation of the site response. The results of the site response analyses are used to develop high- and low-frequency site amplification functions as detailed in Appendix E to this regulatory guide.

4.3 Site Amplification Function

Based on the suite of site response analyses described in Regulatory Position 4.2, site amplification functions are calculated. To determine the UHRS at the free-field ground surface for a specific annual probability of exceedance, multiply the rock-based UHRS by the high-frequency and low-frequency site amplification functions separately, and envelop the two results. If the two controlling earthquake response spectral shapes cover a broad range of frequencies such that when scaled and enveloped they approximate the UHRS, then it is also acceptable to multiply the high- and low-frequency controlling earthquake spectra by the appropriate site amplification function and envelope the results. The surface 1 E-04 and 1 E-05 UHRS are used to determine the performance-based SSE.

5. Performance-Based Site-Specific Earthquake Ground Motion Procedure

5.1 Horizontal Spectrum

The performance-based site-specific earthquake ground motion is developed using a method analogous the development of the design response spectrum (DRS) that achieves the annual FOSID target performance goal (P_F) of 1 E-05, and hazard exceedance probability (H_D) of 1 E-04, described in Chapters 1 and 2 of Reference 3, and also discussed in Section B of this guide. The horizontal site-specific earthquake ground motion is obtained by scaling the site-specific mean UHRS by a design factor (DF), or

Site-Specific Earthquake Ground Motion = UHRS x DF Equation (1)

where UHRS is the mean 1 E-04 UHRS derived in accordance with Regulatory Position 4.4, and DF (from Reference 3) is

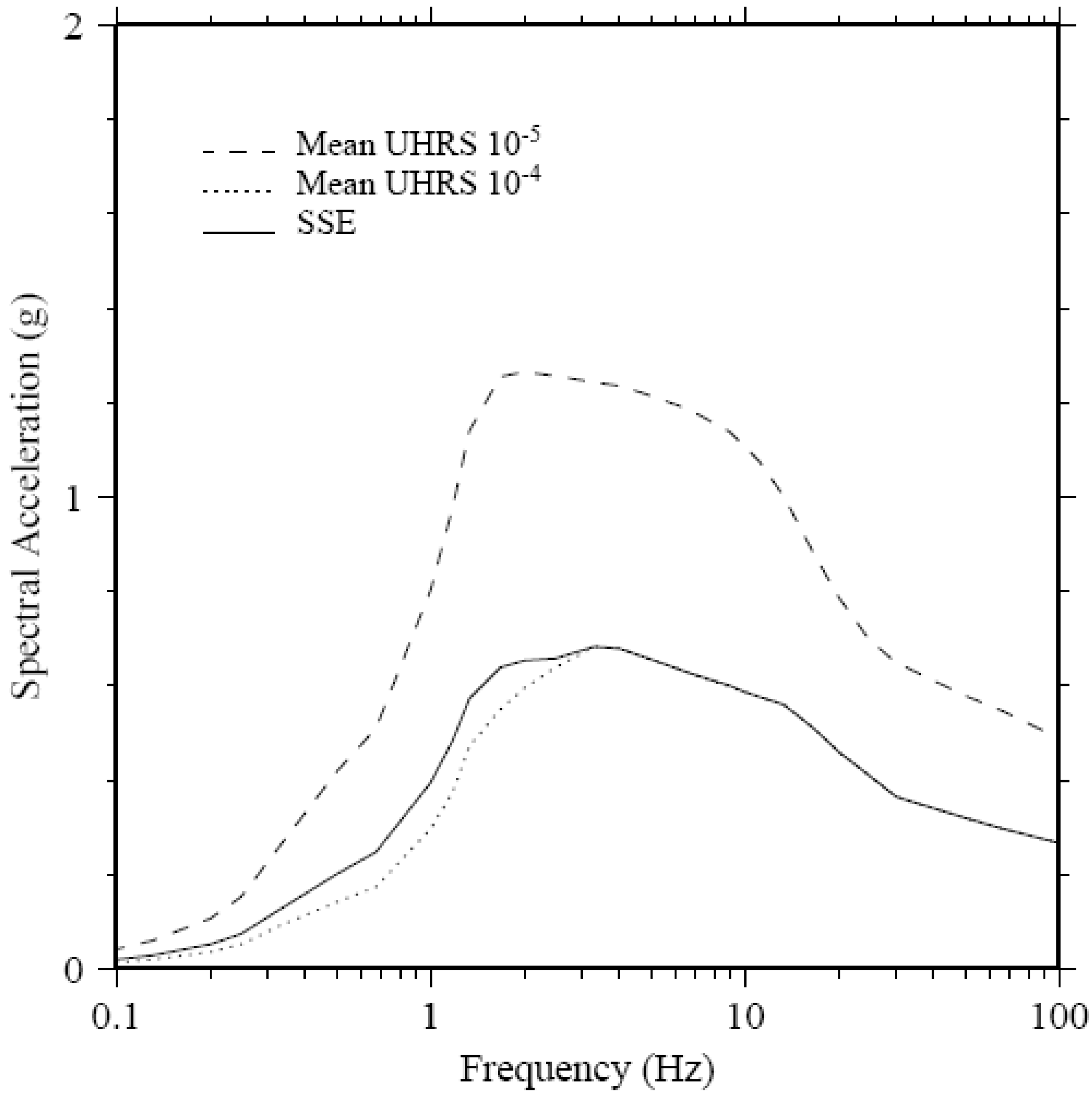
$$DF = \max \{ 1.0, 0.6(A_R)^{0.8} \} \quad \text{Equation (2)}$$

where A_R is the ground motion slope ratio of spectral accelerations, frequency by frequency, from a seismic hazard curve corresponding to a 10-fold reduction in hazard exceedance frequency; therefore,

$$A_R = \text{mean 1 E-05 UHRS} \div \text{mean 1 E-04 UHRS} \quad \text{Equation (3)}$$

Figure 2 provides a comparison of the performance-based site-specific horizontal design response spectrum and the mean 1 E-04 and 1 E-05 UHRS.

The above discussion is based on the assumption that the hazard curves are approximated by a power law equation (i.e., linear on a log-log plot) in the range of 1 E-04 to 1 E-05. If A_R is greater than 4.2, then this assumption is not valid. In these cases, it is acceptable to use a value equal to 45 percent of the mean 1 E-05 UHRS. However, in no case should the site SSE be less than the minimum required by Appendix S to 10 CFR Part 50. (See Regulatory Position 5.4.)



Site-Specific Earthquake Ground Motion

Figure 2. Comparison of the Performance-Base Site Specific Earthquake Ground Motion and the Mean 1E-04 and 1 E-05 UHRS

5.2 Vertical Spectrum

Vertical response spectra are developed be combining the appropriate horizontal response spectra and the most recent V/H response spectral ratios appropriate for either CEUS or WUS sites. Appropriate V/H ratios for CEUS or WUS rock and soil sites should be determined from the most recent attenuation relations. However, as there are currently no CEUS attenuation relations that predict vertical ground motions, appropriate V/H ratios for CEUS rock sites provided in Reference 2 may be used. For CEUS soil sites, References 2 and 18 describe a procedure to determine a WUS-to-CEUS transfer function that may be used to modify the WUS V/H soil ratios. Other methods used to determine V/H ratios may also be appropriate.

5.3 Location of the Site Safe Shutdown Earthquake Ground Motion

The horizontal and vertical SSE are determined in the free field on the ground surface. For sites with one or more thin soil layers near the surface that will be excavated, the SSE is specified on an outcrop or a hypothetical outcrop of competent material ($V_s \geq 1000$ fps) at a free surface.

5.4 Determination of Safe Shutdown Earthquake

The SSE is the vibratory ground motion for which certain structures, systems, and components are designed to remain functional, pursuant to Appendix S to 10 CFR Part 50. The SSE for the site is characterized by both horizontal and vertical free-field ground motion response spectra at the free ground surface. In addition, the horizontal component of motion in the free field at the foundation level of the structures during the SSE must be represented by an appropriate response spectrum with a peak ground acceleration of at least 0.1g.

Development of the SSE will be more fully described in NUREG 0800. However, a conceptual overview of **o**ne method to meet the above criteria based on the site-specific earthquake ground motion is discussed and provided in Figure 3.

Development of the SSE response spectrum begins with the site-specific earthquake ground motion. This motion is developed at the free field ground surface, but must be supplemented by the regulatory requirements defined at the foundation level. The ground motion at the foundation levels consistent with the site-specific earthquake ground motion can be determined by either deconvolution or through a surface-to-foundation depth spectra amplification functions. Surface-to-foundation depth spectral amplification functions are developed by dividing the mean spectral values of the surface motion by the mean spectral value calculated from the output of the site response at the depth of the foundation for each spectral period. This process is analogous to the development of the spectral amplification functions used to compare rock outcrop motions to soil surface motions, as described in Appendix E.

Once the motions at the foundation depth resulting from the site specific earthquake ground motion have been determined, the motions at foundation level are compared against appropriate response spectrum with a peak ground acceleration of at least 0.1g. If necessary, a composite spectrum that envelopes both spectra should be determined. This new composite spectrum is defined at the free field foundation depth and should be used to determine a new free field surface spectrum through either appropriate site response analyses or through the use of the surface-to-foundation depth spectral amplification functions. This new free field surface spectrum is the SSE. In cases where the minimum spectra does not govern, this spectra should be very similar or the same as the site-specific earthquake ground motion determined using this guide.

Once the SSE is developed, it is compared with the seismic design criteria in the design certification documentation.

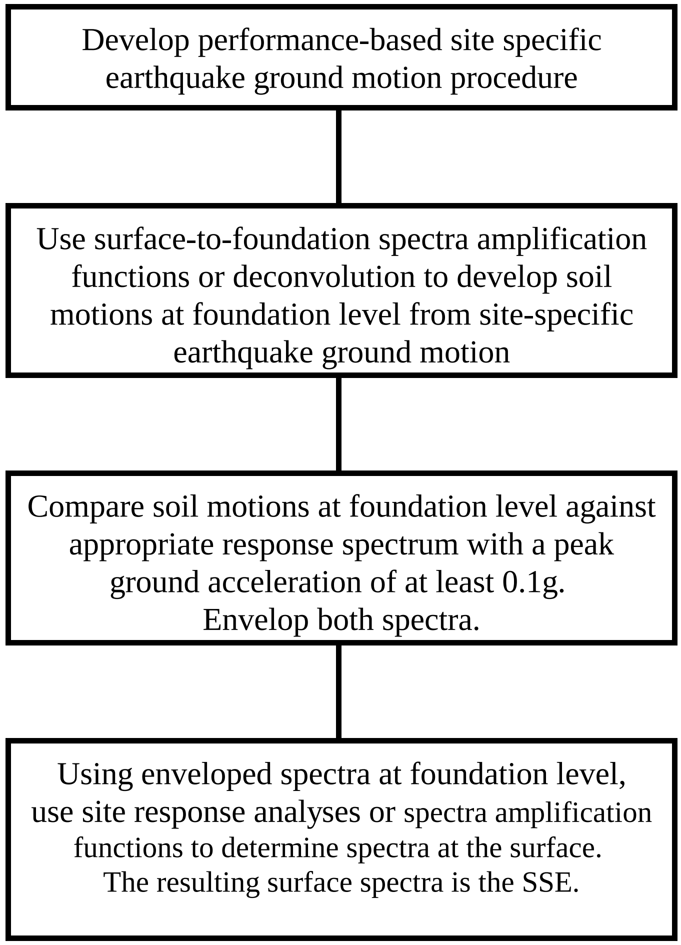


Figure 3. Possible Development Methodology of Safe Shutdown Earthquake

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants regarding the NRC staff's plans for using this draft regulatory guide. No backfitting is intended or approved in connection with its issuance.

This draft regulatory guide identifies methods that the NRC staff considers acceptable for (1) conducting geological, geophysical, seismological, and geotechnical investigations, (2) identifying and characterizing seismic sources, (3) conducting probabilistic seismic hazard analyses, (4) determining seismic wave transmission characteristics of soil and rock sites, and (5) determining a performance-based site-specific earthquake ground motion, for satisfying the requirements of 10 CFR 100.23. A brief overview of techniques to develop the SSE in order to satisfy the requirements of Appendix S to 10 CFR Part 50 is also included in this guide and in NUREG-0800, "Standard Review Plan," Section 3.7.1.

The NRC has issued this draft guide to encourage public participation in its development. Except in those cases in which an applicant or licensee proposes or has previously established an acceptable alternative method for complying with specified portions of the NRC's regulations, the methods to be described in the active guide will reflect public comments and will be used in evaluating submittals in connection with applications for early site permits and combined licenses.

REGULATORY ANALYSIS

1. Statement of the Problem

The U.S. Nuclear Regulatory Commission (NRC) issued Regulatory Guide 1.165, in March 1997. The regulatory guide provides general guidance on procedures acceptable to the NRC staff to satisfy the requirements of 10 CFR 100.23.

The NRC staff recognized the need to provide alternative guidance for incorporating recent developments in ground motion estimation models, updated models for earthquake sources, new methods for determining site response, and new methods for defining a site-specific, performance-based safe shutdown earthquake (SSE) ground motion. Therefore, this draft regulatory guide is being proposed by the NRC staff as an alternative to Regulatory Guide 1.165 to satisfy the requirements of 10 CFR 100.23 and Appendix S to 10 CFR Part 50.

2. Objective

The objective of this regulatory action is to update the NRC's guidance in the area of siting and defining a site-specific, performance-based SSE to give licensees and applicants an opportunity to use state-of-the-art methods that are currently available.

3. Alternatives and Consequences of the Proposed Action

The NRC staff considered the following alternative approaches to the problem of outdated guidance regarding the siting and seismic design:

(1) Do not update Regulatory Guide 1.165.
(2) Update Regulatory Guide 1.165.
(3) Develop a new Regulatory Guide.

3.1 <u>Alternative 1: Do Not Update Regulatory Guide 1.165</u>

Under this alternative, the NRC would not update Regulatory Guide 1.165. Applicants and licensees would continue to rely on the current version of the regulatory guide. This alternative is considered the baseline or "no-action" alternative.

3.2 <u>Alternative 2: Update Regulatory Guide 1.165</u>

Under this alternative, the NRC would update Regulatory Guide 1.165. The update would incorporate improved methods for (1) conducting geological, geophysical, seismological, and geotechnical investigations; (2) identifying and characterizing seismic sources; (3) conducting probabilistic seismic hazard analyses (PSHA); (4) developing ground motion time histories for use in soil response (including a database of time histories for the CEUS and WUS); (5) determining seismic wave transmission (soil amplification) characteristics of soil and rock sites; and (6) defining a site-specific, performance-based SSE. The staff has identified the following consequences associated with adopting Alternative 2:

(1) Applicants and licensees would have guidance on the use of the latest technology available, with consequent improvements in the siting and defining site-specific ground motion for nuclear power plants.

(2) Regulatory efficiency would be improved by reducing uncertainty as to what is acceptable and by encouraging consistency in the siting of nuclear power plants. Benefits to the industry and the NRC will accrue to the extent this occurs. NRC reviews would be facilitated because licensee submittals would be more predictable and analytically consistent.

(3) Both the NRC and the nuclear industry would realize cost savings. From the NRC's perspective, relative to the baseline, the NRC would incur one-time incremental costs to issue the revised regulatory guide. However, the NRC should also realize cost savings associated with the review of licensee submittals. In the staff's view, the ongoing cost savings associated with these reviews should more than offset the one-time cost.

On balance, the NRC staff expects that industry would realize net savings, as the one-time incremental cost to review and comment on the revised regulatory guide would be more than compensated for by the efficiencies (e.g., reduced unnecessary conservatism, followup questions, and revisions) associated with each licensee submission.

(4) Because the new approach is substantially different from the existing Regulatory Guide 1.165 approach, inclusion of both approaches in the same document could be confusing to stakeholders and users of the document.

3.3 Alternative 3: Develop a New Regulatory Guide

Under this alternative, the NRC would develop a new regulatory guide reflecting the improvements to Regulatory Guide 1.165 identified in Alternative 2. In addition to the consequences associated with Alternative 2, the staff has determined that the consequence associated with adopting Alternative 3 is that Regulatory Guide 1.165 would remain as an alternative option for satisfying the requirements of 10 CFR 100.23.

4. Conclusion

Based on this regulatory analysis, the staff recommends that the NRC develop a new regulatory guide. The staff concludes that the proposed action will reduce unnecessary burden on the part of both the NRC and its licensees, while improving the process for siting of nuclear power plants. Furthermore, the staff sees no adverse effects with retaining Regulatory Guide 1.165, an acceptable alternative to the new regulatory guide for satisfying the requirements of 10 CFR 100.23.

BACKFIT ANALYSIS

This regulatory guide gives applicants an opportunity to use currently available state-of-the-art methods for satisfying the requirements of 10 CFR 100.23 and Appendix A to 10 CFR Part 50. As such, this draft regulatory guide does not require a backfit analysis as described in 10 CFR 50.109(c), because it does not impose a new or amended provision in the Commission's rules or a regulatory staff position interpreting the Commission's rules that is either new or different from a previous applicable staff position. In addition, this regulatory guide does not require modification or addition to structures, systems, components, or design of a facility or the procedures or organization required to design, construct, or operate a facility. The application of this regulatory guide is voluntary. An applicant is free to select a preferred method for achieving compliance with a license or the rules or orders of the Commission as described in 10 CFR 50.109(a)(7). Applicants may continue to use Regulatory Guide 1.165, issued March 1997.

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[5] All regulatory guides listed herein were published by the U.S. Nuclear Regulatory Commission. Where an accession number is identified, the specified regulatory guide is available electronically through the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html. All other regulatory guides are available electronically through the Public Electronic Reading Room on the NRC's public Web site, at http://www.nrc.gov/reading-rm/doc-collections/reg-guides/. Single copies of regulatory guides may also be obtained free of charge by writing the Reproduction and Distribution Services Section, ADM, USNRC, Washington, DC 20555-0001, or by fax to (301) 415-2289, or by email to DISTRIBUTION@nrc.gov. Active guides may also be purchased from the National Technical Information Service (NTIS) on a standing order basis. Details on this service may be obtained by contacting NTIS at 5285 Port Royal Road, Springfield, Virginia 22161, online at http://www.ntis.gov, or by telephone at (703) 487-4650. Copies are also available for inspection or copying for a fee from the NRC's Public Document Room (PDR), which is located at 11555 Rockville Pike, Rockville, Maryland; the PDR's mailing address is USNRC PDR, Washington, DC 20555-0001. The PDR can also be reached by telephone at (301) 415-4737 or (800) 397-4205, by fax at (301) 415-3548, and by email to PDR@nrc.gov.

[6] Copies are available for inspection or copying for a fee from the NRC's Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR's mailing address is USNRC PDR, Washington, DC 20555; telephone (301) 415-4737 or (800) 397-4209; fax (301) 415-3548; email PDR@nrc.gov. In addition, copies are available at current rates from the U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20402-9328, telephone (202) 512-1800; or from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161, http://www.ntis.gov, telephone (703) 487-4650.

[7] Copies may be purchased from the American Society for Civil Engineers (ASCE), 1801 Alexander Bell Drive, Reston, VA 20190 [phone: 800-548-ASCE (2723)]. Purchase information is available through the ASCE Web site at http://www.asce.org/bookstore/book.cfm?isbn=0784407622

[8] Copies are available for inspection or copying for a fee from the NRC's Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR's mailing address is USNRC PDR, Washington, DC 20555; telephone (301) 415-4737 or (800) 397-4209; fax (301) 415-3548; email PDR@nrc.gov.

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APPENDIX A

DEFINITIONS

Combined License. A combined construction permit and operating license with conditions for a nuclear power facility issued pursuant to Subpart C of 10 CFR Part 52.

Controlling Earthquakes. The earthquakes used to determine spectral shapes or to estimate ground motions at the site. There may be several controlling earthquakes for a site. As a result of the probabilistic seismic hazard analysis (PSHA), controlling earthquakes are characterized as mean magnitudes and distances derived from a deaggregation analysis of the mean estimate of the PSHA.

Cumulative Absolute Velocity (CAV). For each component of the free-field ground motion, the CAV should be calculated as follows: (1) the absolute acceleration (g units) time-history is divided into 1-second intervals, (2) each 1-second interval that has at least 1 exceedance of 0.025g is integrated over time, and (3) all the integrated values are summed together to arrive at the CAV. The CAV is exceeded if the calculation is greater than 0.16 g-second. The application of the CAV in siting requires the development of a CAV model (Ref. 14) because the PSHA calculation does not use time histories directly.

Deaggregation. The process for determining the fractional contribution of each magnitude-distance pair to the total seismic hazard. To accomplish this, a set of magnitude and distance bins are selected and the annual probability of exceeding selected ground acceleration parameters from each magnitude-distance pair is computed and divided by the total probability for earthquakes.

Design Factor. The ratio between the site-specific earthquake ground motion and the UHRS. The design factor is aimed at achieving the target annual probability of failure associated with the target performance goals.

Early Site Permit. A Commission approval, issued pursuant to Subpart A of 10 CFR Part 52, for a site or sites for one or more nuclear power facilities.

Earthquake Recurrence. The frequency of occurrence of earthquakes as a function of magnitude. Recurrence relationships or curves are developed for each seismic source, and they reflect the frequency of occurrence (usually expressed on an annual basis) of magnitudes up to the maximum, including measures of uncertainty.

Frequency of Onset of Significant Inelastic Deformation (FOSID). The annual probability of the onset of significant inelastic deformation (OSID). OSID is just beyond the occurrence of insignificant (or localized) inelastic deformation, and in this way corresponds to “essentially elastic behavior.” As such, OSID of a structure, system, or component (SSC) can be expected to occur well before seismically induced core damage, resulting in much larger frequencies of OSID than seismic core damage frequency (SCDF) values. In fact, OSID occurs before SSC “failure,” where the term failure refers to impaired functionality.

Ground Motion Slope Ratio. Ratio of the spectral accelerations, frequency by frequency, from a seismic hazard curve corresponding to a 10-fold reduction in hazard exceedance frequency. (See Equation 3 in Regulatory Position 5.1.)

High Confidence in Low Probability of Failure (HCLPF) Capacity. An earthquake acceleration level for which a given component, system, or plant is evaluated as having a 1% failure probability on the mean fragility curve.

Intensity. The intensity of an earthquake is a qualitative description of the effects of the earthquake at a particular location, as evidenced by observed effects on humans, on human-built structures, and on the earth's surface at a particular location. Commonly used scales to specify intensity are the Rossi-Forel, Mercalli, and Modified Mercalli. The Modified Mercalli Intensity (MMI) scale describes intensities with values ranging from I to XII in the order of severity. MMI of I indicates an earthquake that was not felt except by a very few, whereas MMI of XII indicates total damage of all works of construction, either partially or completely.

Magnitude. An earthquake's magnitude is a measure of the strength of the earthquake as determined from seismographic observations and is an objective, quantitative measure of the size of an earthquake. The magnitude can be expressed in various ways based on seismographic records (e.g., Richter Local Magnitude, Surface Wave Magnitude, Body Wave Magnitude, and Moment Magnitude). Currently, the most commonly used magnitude measurement is the Moment Magnitude, M_w, which is based on the seismic moment computed as the rupture force along the fault multiplied by the average amount of slip, and thus is a direct measure of the energy released during an earthquake.

Maximum Magnitude. The maximum magnitude is the upper bound to earthquake recurrence curves.

Mean Site Amplification Function. The mean amplification function is obtained for each controlling earthquake, by dividing the response spectrum from the computed surface motion by the response spectrum from the input hard rock motion, and computing the arithmetic mean of the individual response spectral ratios.

Performance-Based Response Spectrum. A uniform hazard response spectrum (UHRS) that is modified by design factors at various frequencies.

Nontectonic Deformation. Nontectonic deformation is distortion of surface or near-surface soils or rocks that is not directly attributable to tectonic activity. Such deformation includes features associated with subsidence, karst terrain, glaciation or deglaciation, and growth faulting.

Response Spectrum. A plot of the maximum responses (acceleration, velocity, or displacement) of idealized single-degree-of-freedom oscillators as a function of the natural frequencies of the oscillators for a given damping value. The response spectrum is calculated for a specified vibratory motion input at the oscillators' supports.

Ring Area. Annular region bounded by radii associated with the distance rings used in hazard deaggregation (Table D.1, "Recommended Magnitude and Distance Bins," in Appendix D to this regulatory guide).

Safe Shutdown Earthquake Ground Motion (SSE). The vibratory ground motion for which certain structures, systems, and components are designed, pursuant to Appendix S to 10 CFR Part 50, to remain functional. The SSE for the site is characterized by both horizontal and vertical free-field ground motion response spectra at the free ground surface.

Seismic Source. A general term referring to both seismogenic sources and capable tectonic sources.

Capable Tectonic Source. A capable tectonic source is a tectonic structure that can generate both vibratory ground motion and tectonic surface deformation such as faulting or folding at or near the earth's surface in the present seismotectonic regime. It is described by at least one of the following characteristics:

a. presence of surface or near-surface deformation of landforms or geologic deposits of a recurring nature within the last approximately 500,000 years or at least once in the last approximately 50,000 years

b. a reasonable association with one or more moderate to large earthquakes or sustained earthquake activity that are usually accompanied by significant surface deformation

c. a structural association with a capable tectonic source that has characteristics of either item a or b (above), such that movement on one could be reasonably expected to be accompanied by movement on the other

In some cases, the geological evidence of past activity at or near the ground surface along a potential capable tectonic source may be obscured at a particular site. This might occur, for example, at a site having a deep overburden. For these cases, evidence may exist elsewhere along the structure from which an evaluation of its characteristics in the vicinity of the site can be reasonably based. Such evidence is to be used in determining whether the structure is a capable tectonic source within this definition.

Notwithstanding the foregoing paragraphs, the association of a structure with geological structures that are at least pre-Quaternary, such as many of those found in the central and eastern regions of the United States, in the absence of conflicting evidence, will demonstrate that the structure is not a capable tectonic source within this definition.

Seismogenic Source. A seismogenic source is a portion of the earth that is assumed to have a uniform earthquake potential (same expected maximum earthquake and recurrence frequency), distinct from that of surrounding sources**.** A seismogenic source will generate vibratory ground motion but is assumed to not cause surface displacement. Seismogenic sources cover a wide range of seismotectonic conditions, from a well-defined tectonic structure to simply a large region of diffuse seismicity (seismotectonic province).

Seismic Wave Transmission (Site Amplification). The amplification (increase or decrease) of earthquake ground motion by rock and soil near the earth's surface in the vicinity of the site of interest. Topographic effects, the effect of the water table, and basin edge wave-propagation effects are sometimes included under site response.

Spectral Acceleration. Peak acceleration response of an oscillator as a function of period or frequency and damping ratio when subjected to an acceleration time history. It is equal to the peak relative displacement of a linear oscillator of frequency, f, attached to the ground, times the quantity $(2\pi f)^2$. It is expressed in units of gravity (g) or cm/second^2.

Stable Continental Region (SCR). An SCR is composed of continental crust, including continental shelves, slopes, and attenuated continental crust, and excludes active plate boundaries and zones of currently active tectonics directly influenced by plate margin processes. It exhibits no significant deformation associated with the major Mesozoic-to-Cenozoic (last 240 million years) orogenic belts. It excludes major zones of Neogene (last 25 million years) rifting, volcanism, or suturing.

Stationary Poisson Process. A probabilistic model of the occurrence of an event over time (or space) that has the following characteristics: (1) the occurrence of the event in small intervals is constant over time (or space), (2) the occurrence of two (or more) events in a small interval is negligible, and (3) the occurrence of the event in non-overlapping intervals is independent.

Target Performance Goal (P_F). Target annual probability of exceeding the 1 E-05 frequency of onset of significant inelastic deformation (FOSID) limit state.

Tectonic Structure. A large-scale dislocation or distortion, usually within the earth's crust. Its extent may be on the order of tens of meters (yards) to hundreds of kilometers (miles).

Uniform Hazard Response Spectrum (UHRS). A plot of a ground response parameter (for example, spectral acceleration or spectral velocity) that has an equal likelihood of exceedance at different frequencies.

Within Motion. An earthquake record modified for use in a site response model. Within motions are developed through deconvolution of a surface recording to account for the properties of the overburden material at the level at which the record is to be applied. The within motion can also be called the "bedrock motion" if it occurs at a high-impedance boundary where rock is first encountered.

APPENDIX B

ABBREVIATIONS

A	peak ground acceleration
A_R	ground motion slope ratio
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Materials
CAV	cumulative absolute velocity
CP	construction permit
CEUS	central and eastern United States
D	distance
D	peak ground displacement
DF	design factor
EPRI	Electric Power Research Institute
FOSID	frequency of onset of significant inelastic deformation
HCLPF	high-confidence-low-probability-of-failure (1% mean probability of failure)
H_D	mean annual hazard exceedance frequency
LLNL	Lawrence Livermore National Laboratory
M	magnitude
MMI	Modified Mercalli Intensity
NRC	U.S. Nuclear Regulatory Commission
OL	operating license
OMB	Office of Management and Budget
OSID	onset of significant inelastic deformation
P_F	target performance goal
PGA	peak ground acceleration
PGV	peak ground velocity
PSHA	probabilistic seismic hazard analysis
R_P	probability ratio
SCDF	seismic core damage frequency
SCR	stable continental region
SDC	seismic design category
SRP	Standard Review Plan (NUREG-0800)
SSCs	structures, systems, and components
SSE	safe shutdown earthquake ground motion
Standard	ASCE/SEI Standard 43-05

UHRS	uniform hazard response spectrum
USNRC	U.S. Nuclear Regulatory Commission
V	peak ground velocity
V/H	ratio of vertical to horizontal spectral accelerations
V_s	shear wave velocity
WUS	western United States

APPENDIX C

INVESTIGATIONS TO CHARACTERIZE SITE GEOLOGY, SEISMOLOGY AND GEOPHYSICS

C.1 Introduction

As characterized for use in probabilistic seismic hazard analyses (PSHA), seismogenic sources are zones within which future earthquakes are likely to occur. Geological, seismological, and geophysical investigations provide the information needed to identify and characterize source zone parameters, such as size and geometry, and to estimate earthquake recurrence rates and maximum magnitudes. The amount of data available about earthquakes and their causative sources varies substantially between the western United States (WUS) (west of the Rocky Mountain front) and the central and eastern United States (CEUS), or stable continental region (east of the Rocky Mountain front). Furthermore, there are variations in the amount and quality of data within these regions.

Seismogenic sources in active tectonic regions such as the WUS are generally readily identified because of their relatively high activity rate. In the CEUS, identifying seismogenic sources is more difficult because their activity rate is relatively low and because most seismic sources are covered by thick deposits. However, several significant tectonic structures exist and some of these have been interpreted as seismogenic sources (e.g., the New Madrid fault zone, Nemaha Ridge, and Meers fault).

In the CEUS, it is most likely that the determination of the properties of the seismogenic source, whether it is a tectonic structure or a seismotectonic province, will be inferred rather than demonstrated by strong correlations with seismicity or geologic data. Moreover, it is not generally known what relationships exist between observed tectonic structures in a seismic source within the CEUS and the current earthquake activity that may be associated with that source. The historical seismicity record, the results of regional and site studies, and expert judgment play key roles in characterizing a source zone. If, on the other hand, strong correlations and data exist suggesting a relationship between seismicity and seismic sources, approaches used for more active tectonic regions can be applied. Reference C.1 may be used to assess potential for large earthquakes.

The primary objective of geological, seismological, and geophysical investigations is to develop an up-to-date, site-specific earth science database that supports site characterization and a PSHA. The results of these investigations will also be used to assess whether new data and their interpretation are consistent with the information used in accepted probabilistic seismic hazard studies. If the new data, such as new seismic sources and new ground motion attenuation relationships, are consistent with the existing earth science database, updating or modification of the hazard analysis is not required. It will be necessary to update seismic sources and ground motion attenuation relationships for sites where there is significant new information provided by the site investigation.

The following are to be evaluated for seismic source characterization:

- Seismic source location and geometry (location and extent, both surface and subsurface). This evaluation will normally require interpretations of available geological, geophysical, and seismological data in the source region by multiple experts or a team of experts. The evaluation should include interpretations of the seismic potential of each source and relationships among seismic sources in the region to express uncertainty in the evaluations. Seismic source evaluations generally develop four types of sources: (1) fault sources, (2) area sources representing concentrated historic seismicity not associated with known tectonic structure,

(3) area sources representing geographic regions with similar tectonic histories, type of crust, and structural features, and (4) background sources. Background sources are generally used to express uncertainty in the overall seismic source configuration interpreted for the site region. Acceptable approaches for evaluating and characterizing uncertainties for input to a seismic hazard calculation are contained in NUREG/CR-6372 (Ref. C.2).

- Evaluations of earthquake recurrence for each seismic source, including recurrence rate and recurrence model. These evaluations normally draw most heavily on historical and instrumental seismicity associated with each source and paleoearthquake information. Preferred methods and approaches for evaluating and characterizing uncertainty in earthquake recurrence generally will depend on the type of source. Acceptable methods are described in NUREG/CR-6372 (Ref. C.2).

- Evaluations of the maximum earthquake magnitude for each seismic source. These evaluations will draw on a broad range of source-specific tectonic characteristics, including tectonic history and available seismicity data. Uncertainty in this evaluation should normally be expressed as a maximum magnitude distribution. Preferred methods and information for evaluating and characterizing maximum earthquakes for seismic sources vary with the type of source. Acceptable methods are contained in NUREG/CR-6372 (Ref. C.2).

- Other evaluations, depending on the geologic setting of a site, such as local faults that have a history of Quaternary (last 2 million years) displacements, sense of slip on faults, fault length and width, area of faults, age of displacements, estimated displacement per event, estimated earthquake magnitude per offset event, orientations of regional tectonic stresses with respect to faults, and the possibility of seismogenic folds. Capable tectonic sources are not always exposed at the ground surface (such as blind thrust faults) in the WUS as demonstrated by the buried reverse causative faults of the 1983 Coalinga, 1988 Whittier Narrows, l989 Loma Prieta, and 1994 Northridge earthquakes. These examples emphasize the need to conduct thorough investigations not only at the ground surface but also in the subsurface to identify structures at seismogenic depths. Regional topographic features should also be closely studied. Whenever faults or other structures are encountered at a site (including sites in the CEUS) in either outcrop or excavations, it is necessary to perform adequately detailed specific investigations to determine whether or not they are seismogenic or may cause surface deformation at the site. Acceptable methods for performing these investigations are contained in NUREG/CR-5503 (Ref. C.3).

C.2. Investigations To Evaluate Seismic Sources

C.2.1 <u>General</u>

Investigations of the site and region around the site are necessary to identify capable tectonic sources and to determine their potential for generating earthquakes and causing surface deformation. If it is determined that surface deformation need not be taken into account at the site, sufficient data to clearly justify the determination should be presented in the application for an early site permit or combined license. Generally, any tectonic deformation at the earth’s surface within the Site Area [8 km (5 mi)of the site] will require detailed examination to determine its significance. Potentially active tectonic deformation within the seismogenic zone beneath a site will have to be assessed using geological, geophysical and seismological methods to determine its significance. Engineering solutions are generally available to mitigate the potential vibratory effects of earthquakes through design. However, engineering solutions cannot always be demonstrated to be adequate for mitigation of the effects of permanent ground displacement phenomena such as surface faulting or folding, subsidence, or ground collapse. For this reason, it is prudent to select an alternative site when the potential exists for permanent ground displacement at the proposed site (Ref. C.4).

The level of detail for investigations should be governed by knowledge of the current and late Quaternary tectonic regime and the geological complexity of the site and region. The investigations for determining seismic sources should be carried out in all the following levels, with areas described by radii of 320 km (200 mi) (Site Region), 40 km (25 mi) (Site Vicinity), and 8 km (5 mi) (Site Area) and 1 km (0.6 mi) (Site Location) from the site. The investigations should provide increasingly detailed information as they proceed from the regional level down to the site (e.g., from Site Region to Site Location). Whenever faults or other structures are encountered at a site in either outcrop or excavations, it is necessary to perform many of the investigations described below to determine whether or not they are capable tectonic sources.

C.2.1.1 ***Site Region Investigations [within radii of 320 km (200 mi) – 40 km (25 mi) of the site]***

The Site Region investigations should be planned to identify seismic sources and describe the Quaternary tectonic regime. The data should be presented at a scale of 1:500,000 or larger. The investigations are not expected to be extensive or in detail, but should include a comprehensive literature review supplemented by focused geological reconnaissances based on the results of the literature study (including topographic, geologic, aeromagnetic, and gravity maps, and airphotos). Some detailed investigations at specific locations within the region may be necessary if potential seismic sources that may be significant for determining the safe shutdown earthquake ground motion (SSE), are identified.

The large size of the area for the regional investigations is recommended because of the possibility that all significant seismic sources, or alternative configurations, may not have been captured or enveloped by previous source databases, such as the Lawrence Livermore National Laboratory (LLNL)/Electric Power Research Institute (EPRI) database. Thus, it will increase the chances of (1) identifying evidence for unknown seismic sources that might extend close enough for earthquake ground motions generated by that source to affect the site, and (2) confirming the PSHA's database. Furthermore, because of the relative rarity of seismic activity in the CEUS, the area should be large enough to include as many historical and instrumentally recorded earthquakes for analysis as reasonably possible. The specified area of study is expected to be large enough to incorporate any previously identified sources that could be analogous to sources that may underlie or be relatively close to the site. In past licensing activities for sites in the CEUS, it has often been necessary, because of the absence of datable horizons overlying bedrock, to extend investigations out many tens or hundreds of kilometers from the site along a structure or to an outlying analogous structure to locate overlying datable strata or unconformities so that geochronological methods could be applied. This procedure has also been used to estimate the age of an undatable seismic source in the Site Vicinity by relating its time of last activity to that of a similar, previously evaluated structure, or a known tectonic episode, the evidence of which may be many tens or hundreds of kilometers away.

It is necessary to evaluate the geological, seismological, and geophysical data obtained from the site-specific investigations to demonstrate that the data are sufficient and consistent with the PSHA methodology. Specifically, the evaluation may need to include but not limited to seismic source characterization, ground motion attenuation relationships and other PSHA-related contents, such as low-magnitude threshold and magnitude conversion relationships. If new information identified by the site-specific investigations were to result in a significant increase in the hazard estimate for a site, and if this new information were validated by a strong technical basis, the PSHA might have to be modified to incorporate the new technical information. Using sensitivity studies, it may also be possible to justify a lower hazard estimate with an exceptionally strong technical basis. However, it is expected that large uncertainties in estimating seismic hazard in the CEUS will continue to exist in the future, and substantial delays in the licensing process will result from trying to justify a lower value with respect to a specific site.

C.2.1.2 *Site Vicinity Investigations [within radii of 40 km (25 mi) – 8 km (5 mi) of the site]*

Reconnaissance-level investigations, which may need to be supplemented at specific locations by more detailed explorations such as geologic mapping, geophysical surveying, borings, and trenching, should be conducted for the Site Vicinity; the data should be presented at a scale of 1:50,000 or larger.

C.2.1.3 *Site Area Investigations [within radii of 8 km (5 mi) – 1 km (0.6 mi) of the site]*

Detailed investigations should be carried out within the Site Area, and the resulting data presented at a scale of 1:5,000 or larger. The level of investigations should be in sufficient detail to delineate the geology and the potential for tectonic deformation at or near the ground surface. The investigations should use the methods described in the following subsections that are appropriate for the tectonic regime to characterize seismic sources.

The areas of investigations may be asymmetrical and may cover larger areas than those described above in regions of late Quaternary activity, regions with high rates of historical seismic activity (felt or instrumentally recorded data), or sites that are located near a capable tectonic source such as a fault zone.

C.2.2 <u>Contents of Site Vicinity and Site Area Investigations</u>

The following methods are suggested but they are not all-inclusive and investigations should not be limited to them. Some procedures will not be applicable to every site, and situations will occur that require investigations that are not included in the following discussion. It is anticipated that new technologies will be available in the future that will be applicable to these investigations.

C.2.2.1 *Surface Investigations*

Surface exploration to assess the geology and geologic structure of the Site Area is dependent on the Site Location and may be carried out with the use of any appropriate combination of the geological, geophysical, seismological, and geotechnical engineering techniques summarized in the following paragraphs. However, not all of these methods must be carried out at a given site.

C.2.2.1.1 Geological interpretations should be performed of aerial photographs and other remote-sensing imagery, as appropriate for the particular site conditions, to assist in identifying rock outcrops, faults and other tectonic features, fracture traces, geologic contacts, lineaments, soil conditions, and evidence of landslides or soil liquefaction.

C.2.2.1.2 Mapping topographic, geomorphic, and hydrologic features should be performed at scales and with contour intervals suitable for analysis and descriptions of stratigraphy (particularly Quaternary), surface tectonic structures such as fault zones, and Quaternary geomorphic features. For coastal sites, or sites located near lakes or rivers, this includes topography, geomorphology (particularly mapping marine and fluvial terraces), bathymetry, submarine landslides, geophysics (such as seismic reflection), and hydrographic surveys to the extent needed to describe the site area features.

C.2.2.1.3 Vertical crustal movements should be evaluated using (1) geodetic land surveying and (2) geological analyses (such as analysis of regional dissection and degradation patterns), shorelines, fluvial adjustments (such as changes in stream longitudinal profiles or terraces), and other long-term changes (such as elevation changes across lava flows).

C.2.2.1.4 Analysis should be performed to determine the tectonic significance of offset, displaced, or anomalous landforms such as displaced stream channels or changes in stream profiles or the upstream migration of knickpoints; abrupt changes in fluvial deposits or terraces; changes in paleo-channels across a fault; or uplifted, down-dropped, or laterally displaced marine terraces.

C.2.2.1.5 Analysis should be performed to determine the tectonic significance of Quaternary sedimentary deposits within or near tectonic zones, such as fault zones, including (1) fault-related or fault-controlled deposits such as sag ponds, graben fill deposits, and colluvial wedges formed by the erosion of a fault paleo-scarp and (2) non-fault-related, but offset, deposits such as alluvial fans, debris cones, fluvial terrace, and lake shoreline deposits.

C.2.2.1.6 Identification and analysis should be performed of deformation features caused by vibratory ground motions, including seismically induced liquefaction features (sand boils, explosion craters, lateral spreads, settlement, soil flows), mud volcanoes, landslides, rockfalls, deformed lake deposits or soil horizons, shear zones, cracks, or fissures.

C.2.2.1.7 Analysis should be performed of fault displacements, including the interpretion of the morphology of topographic fault scarps associated with or produced by surface rupture. Fault scarp morphology is useful in estimating the age of last displacement [in conjunction with the appropriate geochronological methods described in NUREG/CR-5562 (Ref. C.5)], approximate magnitude of the associated earthquake, recurrence intervals, slip rate, and the nature of the causative fault at depth.

C.2.2.2 *Subsurface Investigation Contents*

Subsurface investigations at the site to identify and describe potential seismic sources or capable tectonic sources and to obtain required geotechnical information are described in Regulatory Guide 1.132 (Ref. C.6). The investigations include, but may not be confined to, the following:

C.2.2.2.1 Geophysical investigations useful in the past include magnetic and gravity surveys, seismic reflection and seismic refraction surveys, bore-hole geophysics, electrical surveys, and ground-penetrating radar surveys.

C.2.2.2.2 Core borings to map subsurface geology and obtain samples for testing such as determining the properties of the subsurface soils and rocks and geochronological analysis.

C.2.2.2.3 Excavating and logging of trenches across geological features to obtain samples for the geochronological analysis of those features.

C.2.2.2.4 At some sites, deep unconsolidated material/soil, bodies of water, or other material may obscure geologic evidence of past activity along a tectonic structure. In such cases, the analysis of evidence elsewhere along the structure can be used to evaluate its characteristics in the vicinity of the site.

In the CEUS it may not be possible to reasonably demonstrate the age of youngest activity on a tectonic structure with adequate deterministic certainty. In such cases, the uncertainty should be quantified; the NRC staff will accept evaluations using the methods described in NUREG/CR-5503 (Ref. C.3). A demonstrated tectonic association of such structures with geologic structural features or tectonic processes that are geologically old (at least pre-Quaternary) should be acceptable as an age indicator in the absence of conflicting evidence.

C.2.3 Site Location Investigations [within 1 km (0.6 mi)]

Data from Site Location investigations should be presented at a scale of 1:500 or larger. Important aspects of the site investigations are the excavation and logging of exploratory trenches and the mapping of the excavations for the plant structures, particularly those that are characterized as Seismic Category I. In addition to geological, geophysical, and seismological investigations, detailed geotechnical engineering investigations as described in Regulatory Guide 1.132 (Ref. C.6), should be conducted at the site.

C.2.4 Surface-Fault Rupture and Associated Deformation at the Site

Avoid a site that has a potential for fault rupture at or near the ground surface and associated deformation. Where it is determined that surface deformation need not be taken into account, sufficient data or detailed studies to reasonably support the determination should be presented. The presence or absence of Quaternary faulting at the site needs to be evaluated to determine whether there is a potential hazard that is caused by surface faulting. The potential for surface fault rupture should be characterized by evaluating (1) the location and geometry of faults relative to the site, (2) the nature and amount of displacement (sense of slip, cumulative slip, slip per event, and nature and extent of related folding and/or secondary faulting), and (3) the likelihood of displacement during some future period of concern (recurrence interval, slip rate, and elapsed time since the most recent displacement). Acceptable methods and approaches for conducting these evaluations are described in NUREG/CR-5503 (Ref. C.3); acceptable geochronology dating methods are described in NUREG/CR-5562 (Ref. C.5).

For assessing the potential for fault displacement, the details of the spatial pattern of the fault zone (e.g., the complexity of fault traces, branches, and en echelon patterns) may be important as they may define the particular locations where fault displacement may be expected in the future. The amount of slip that might be expected to occur can be evaluated directly based on paleoseismic investigations or it can be estimated indirectly based on the magnitude of the earthquake that the fault can generate.

Both non-tectonic and tectonic deformation can pose a substantial hazard to a nuclear power plant, but there are likely to be differences in the approaches used to resolve the issues raised by the two types of phenomena. Therefore, non-tectonic deformation should be distinguished from tectonic deformation at a site. In past nuclear power plant licensing activities, surface displacements caused by phenomena other than tectonic phenomena have been confused with tectonically induced faulting. These structures, such as those found in karst terrain, and growth faulting, which occurs in the Gulf Coastal Plain or in other deep soil regions, cause extensive subsurface fluid withdrawal.

Glacially induced faults generally do not represent a deep-seated seismic or fault displacement hazard because the conditions that created them are no longer present. However, residual stresses from Pleistocene glaciation may still be present in glaciated regions, although they are of less concern than active tectonically induced stresses. These features should be investigated with respect to their relationship to current in situ stresses.

The nature of faults related to collapse features can usually be defined through geotechnical investigations and can either be avoided or, if feasible, adequate engineering fixes can be provided.

Large, naturally occurring growth faults as those found in the coastal plain of Texas and Louisiana can pose a surface displacement hazard, even though offset most likely occurs at a much less rapid rate than that of tectonic faults. They are not regarded as having the capacity to generate damaging vibratory ground motion, can often be identified and avoided in siting, and their displacements can be monitored. Some growth faults and antithetic faults related to growth faults and fault zones should be investigated in regions where growth faults are known to be present. Local human-induced growth faulting can be monitored and controlled or avoided.

If questionable features cannot be demonstrated to be of non-tectonic origin, they should be treated as tectonic deformation.

C.2.5 Site Geotechnical Investigations and Evaluations

C.2.5.1 *Geotechnical Investigations*

The geotechnical investigations should include, but not necessarily be limited to, (1) defining site soil and near-surface geologic strata properties as may be required for hazard evaluations, engineering analyses, and seismic design; (2) evaluating the effects of local soil and site geologic strata on ground motion at the ground surface; (3) evaluating dynamic properties of the near-surface soils and geologic strata; (4) conducting soil-structure interaction analyses; and (5) assessing the potential for soil failure or deformation induced by ground shaking (liquefaction, differential compaction, and land sliding).

Subsurface conditions should be investigated by means of borings, soundings, well logs, exploratory excavations, sampling, geophysical methods (e.g., cross-hole, down-hole, and geophysical logging) that adequately assess soil and ground-water conditions and other methods described in NUREG/CR-5738 (Ref. C.7). Appropriate investigations should be made to determine the contribution of the subsurface soils and rocks to the loads imposed on the structures.

A laboratory testing program should be carried out to identify and classify the subsurface soils and rocks and to determine their physical and engineering properties. Laboratory tests for both static and dynamic properties (e.g., shear modulus, damping, liquefaction resistance, etc.) are generally required. The dynamic property tests should include cyclic triaxial tests, cyclic simple shear tests, cyclic torsional shear tests, and resonant column tests, as appropriate. Both static and dynamic tests should be conducted as recommended in American Society for Testing and Materials (ASTM) standards or test procedures acceptable to the staff. The ASTM specification numbers for static and dynamic laboratory tests can be found in the annual books of ASTM Standards, Volume 04.08. Sufficient laboratory test data should be obtained to allow for reasonable assessments of mean values of soil properties and their potential variability.

C.2.5.2 *Ground Failure Evaluations*

Liquefaction is a soil behavior phenomenon in which cohesionless soils (sand, silt, or gravel) under saturated conditions lose a substantial part or all of their strength because of high pore water pressures generated in the soils by strong ground motions induced by earthquakes. Potential effects of liquefaction include reduction in foundation bearing capacity, settlements, land sliding and lateral movements, flotation of lightweight structures (such as tanks) embedded in the liquefied soil, and increased lateral pressures on walls retaining liquefied soil. Guidance in Regulatory Guide 1.198, "Procedures and Criteria for Assessing Seismic Soil Liquefaction at Nuclear Power Plant Sites" (Ref. C.8), should be used for evaluating the site for liquefaction potential.

Investigations of liquefaction potential typically involve both geological and geotechnical engineering assessments. The parameters controlling liquefaction phenomena are (1) the lithology of the soil at the site, (2) the ground water conditions, (3) the behavior of the soil under dynamic loadings, and (4) the potential severity of the vibratory ground motion.

C.3 Evaluation of New Information Obtained from the Site-specific Investigations

The first step inreviewing the new information obtained from the site-specific investigations withprevious interpretations is determining whether thefollowing existing parameters are consistent with the new information: (1) the range of seismogenic sources as interpreted by the seismicity experts or teams involved in the study, (2) the range of seismicity rates for the region around the site as interpreted by the seismicity experts or teams involved in the studies, (3) the range of maximum magnitudes determined by the seismicity experts or teams, and (4) attenuation relations. The new information is considered not significant and no further evaluation is needed if it is consistent with the assumptions used in the PSHA, no additional alternative seismic sources or seismic parameters are needed, or it supports maintaining the site mean seismic hazard.

APPENDIX C REFERENCES

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1 Copies are available for inspection or copying for a fee from the NRC's Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR's mailing address is USNRC PDR, Washington, DC 20555; telephone (301) 415-4737 or (800) 397-4209; fax (301) 415-3548; email PDR@nrc.gov. In addition, copies are available at current rates from the U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20402-9328, telephone (202) 512-1800; or from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161, http://www.ntis.gov, telephone (703) 487-4650.

2 All regulatory guides listed herein were published by the U.S. Nuclear Regulatory Commission. Where an ADAMS accession number is identified, the specified regulatory guide is available electronically through the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html. All other regulatory guides are available electronically through the Public Electronic Reading Room on the NRC's public Web site, at http://www.nrc.gov/reading-rm/doc-collections/reg-guides/. Single copies of regulatory guides may also be obtained free of charge by writing the Reproduction and Distribution Services Section, ADM, USNRC, Washington, DC 20555-0001, or by fax to (301) 415-2289, or by email to DISTRIBUTION@nrc.gov. Active guides may also be purchased from the National Technical Information Service (NTIS) on a standing order basis. Details on this service may be obtained by contacting NTIS at 5285 Port Royal Road, Springfield, Virginia 22161, online at http://www.ntis.gov, or by telephone at (703) 487-4650. Copies are also available for inspection or copying for a fee from the NRC's Public Document Room (PDR), which is located at 11555 Rockville Pike, Rockville, Maryland; the PDR's mailing address is USNRC PDR, Washington, DC 20555-0001. The PDR can also be reached by telephone at (301) 415-4737 or (800) 397-4205, by fax at (301) 415-3548, and by email to PDR@nrc.gov.

APPENDIX D

DETERMINATION OF CONTROLLING EARTHQUAKES AND DEVELOPMENT OF SEISMIC HAZARD INFORMATION BASE

D.1 Introduction

This appendix elaborates on the steps described in Regulatory Position 3 of this regulatory guide for determining the controlling earthquakes used to develop an appropriate ground motion for the site response analysis. The controlling earthquakes are developed from the deaggregation of the probabilistic seismic hazard analysis (PSHA) results at ground motion levels corresponding to the annual frequencies of 1 E-04, 1 E-05, and 1 E-06. The deaggregation of the PSHA defines the contribution of individual magnitude and distance ranges to the overall seismic hazard and results in the magnitude and distance values of the controlling earthquakes at the average of 1 and 2.5 Hz and the average of 5 and 10 Hz.

Using the controlling earthquakes, Regulatory Position 4 and Appendix E to this regulatory guide describe a procedure for determining the appropriate ground motion for the site response analysis to determine the performance-based safe shutdown earthquake ground motion (SSE).

D.2 Procedure To Determine Controlling Earthquakes

The following approach is acceptable to the Nuclear Regulatory Commission (NRC) staff for determining the controlling earthquakes. This procedure is based on a deaggregation of the probabilistic seismic hazard in terms of earthquake magnitudes and distances. When the controlling earthquakes have been obtained, the site specific earthquake ground motion can be developed according to the procedures described in Appendix E. The SSE response spectrum can then be determined according to the procedures described in Regulatory Position 5.

Step 1

Perform a site-specific PSHA. The PSHA methodology attributes and results described in Regulatory Positions 3.3 and 3.4 of this regulatory guide are summarized as follows:

- Perform the PSHA for actual or assumed rock conditions with up-to-date interpretations of earthquake sources, earthquake recurrence, and strong ground motion estimation using original or updated sources as determined in Regulatory Positions 3.1 and 3.2.
- CAV filtering can be used in place of a lower-bound magnitude cutoff (Ref. D.1).
- Conduct the hazard assessment at a minimum of 30 frequencies, approximately equally spaced on a logarithmic frequency axis between 100 and 0.1Hz.
- Report fractile hazard curves at the following fractile levels (p) for each ground motion parameter: 0.05, 0.16, 0.50, 0.84, and 0.95, as well as the mean. Report the fractile hazard curves in tabular as well as graphical format.
- Determine the mean uniform hazard response spectra (UHRS) for annual exceedance frequencies of 1 E-04, 1 E-05, and 1 E-06.

Steps 2 through 7 are repeated at annual probability levels corresponding to 1 E-04, 1 E-05, and 1 E-06. The resultant hazard curves for the annual probability level of 1 E-05 are shown in Figure D.1.

Step 2

(a) Using the annual probability levels of 1 E-04, 1 E-05, and 1 E-06, determine the ground motion levels for the spectral accelerations at 1, 2.5, 5, and 10 Hz from the total mean hazard obtained in Step 1.

(b) Calculate the average of the ground motion level for the 1 and 2.5 Hz and the 5 and 10 Hz spectral acceleration pairs.

Step 3

Perform a deaggregation of the PSHA for each of the spectral accelerations and annual probability levels as enumerated in Step 2, and provide a table (such as illustrated in Table D.1[1]) for each of the 12 cases. The deaggregation is performed to obtain the relative contribution to the hazard for each of the magnitude-distance bins for each case.

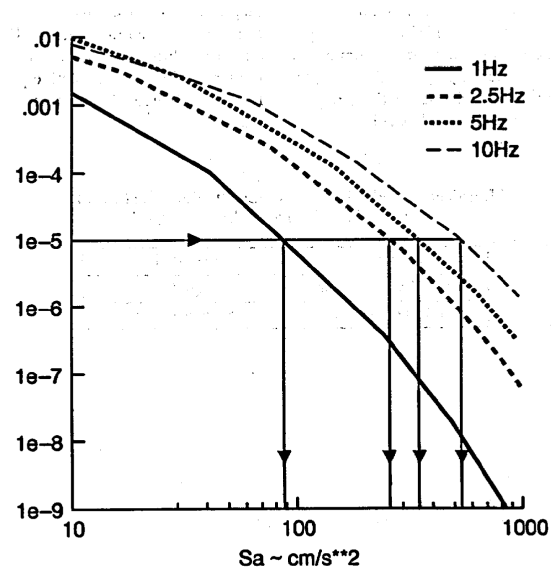

Figure D.1. Total Mean Hazard Curves

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1 The recommended magnitude and distance bins and procedure used to establish controlling earthquakes were developed for application in the CEUS, where the nearby earthquakes generally control the response in the 5 to 10 Hz frequency range, and larger but distant events can control the lower frequency range. For other situations, alternative binning schemes as well as a study of contributions from various bins will be necessary to identify controlling earthquakes, consistent with the distribution of the seismicity.

Table D.1
Recommended Magnitude and Distance Bins

Moment Magnitude Range of Bins					
Distance Range of Bin (km)	**5 – 5.5**	**5.5 – 6**	**6 – 6.5**	**6.5 – 7**	**>7**
0 – 15					
15 – 25					
25 – 50					
50 – 100					
100 – 200					
200 – 300					
>300					

Step 4

If the deaggregated results for each of the 12 cases is not in terms of the fractional contribution to the total hazard then perform Step 4 as described below. Otherwise, average the low-frequency (1 and 2.5 Hz) and high-frequency (5 and 10 Hz) deaggregation results.

From the deaggregated results of Step 3, the mean annual probability of exceeding the ground motion levels of Step 2(a) (spectral accelerations at 1, 2.5, 5, and 10 Hz) are determined for each magnitude-distance bin. These values are denoted by H_{mdf}.

Using H_{mdf} values, the fractional contribution of each magnitude and distance bin to the total hazard for the average of 1 and 2.5 Hz, $P(m,d)_1$, is computed according to the following:

$$P(m,d)_1 = [(\sum_{f=1,2} H_{mdf}) / 2] \div [\sum_m \sum_d (\sum_{f=1,2} H_{mdf}) / 2] \qquad \text{(Equation 1)}$$

where f = 1 and f = 2 represent the ground motion measure at 1 and 2.5 Hz, respectively.

The fractional contribution of each magnitude and distance bin to the total hazard for the average of 5 and 10 Hz, $P(m,d)_2$, is computed according to the following:

$$P(m,d)_2 = [(\sum_{f=1,2} H_{mdf}) / 2] \div [\sum_m \sum_d (\sum_{f=1,2} H_{mdf}) / 2] \qquad \text{(Equation 2)}$$

where f = 1 and f = 2 represent the ground motion measure at 5 and 10 Hz, respectively.

Step 5

Review the magnitude-distance distribution for the average of 1 and 2.5 Hz to determine whether the contribution to the hazard for distances of 100 kilometer (km) (63 mi) or greater is substantial (on the order of 5 percent or greater).

If the contribution to the hazard for distances of 100 km (63 mi) or greater exceeds 5 percent, additional calculations are needed to determine the controlling earthquakes using the magnitude-distance distribution for distances greater than 100 km (63 mi). This distribution, $P > 100\,(m,d)_1$, is defined by the following:

$$P > 100\,(m,d)_1 = [\, P(m,d)_1 \,] \div [\, \sum_{m} \sum_{d > 100} P(m,d)_1 \,] \quad \text{(Equation 3)}$$

The purpose of this calculation is to identify a distant, larger event that may control low-frequency content of a response spectrum.

The distance of 100 km (63 mi) is chosen for CEUS sites. However, for all sites the results of full magnitude-distance distribution should be carefully examined to ensure that proper controlling earthquakes are clearly identified.

Step 6

Calculate the mean magnitude and distance of the controlling earthquake associated with the ground motions determined in Step 2 for the average of 5 and 10 Hz. The following relation is used to calculate the mean magnitude using results of the entire magnitude-distance bins matrix:

$$M_c\,(5 - 10\text{ Hz}) = \sum_{m} m \sum_{d} P(m,d)_2 \quad \text{(Equation 4)}$$

where m is the central magnitude value for each magnitude bin.

The mean distance of the controlling earthquake is determined using results of the entire magnitude-distance bins matrix:

$$\text{Ln}\,\{D_c\,(5 - 10\text{ Hz})\} = \sum_{d} \text{Ln}(d) \sum_{m} P(m,d)_2 \quad \text{(Equation 5)}$$

where d is the centroid distance value for each distance bin.

Step 7

If the contribution to the hazard calculated in Step 5 for distances of 100 km (63 mi) or greater exceeds 5 percent for the average of 1 and 2.5 Hz, calculate the mean magnitude and distance of the controlling earthquakes associated with the ground motions determined in Step 2 for the average of 1 and 2.5 Hz. The following relation is used to calculate the mean magnitude using calculations based on magnitude-distance bins greater than distances of 100 km (63 mi) as discussed in Step 5:

$$M_c\,(1 - 2.5\text{ Hz}) = \sum_{m} m \sum_{d > 100} P > 100\,(m,d)_1 \quad \text{(Equation 6)}$$

where m is the central magnitude value for each magnitude bin.

The mean distance of the controlling earthquake is based on magnitude-distance bins greater than distances of 100 km (63 mi) as discussed in Step 5 and determined according to the following:

$$\text{Ln}\,\{D_c\,(1 - 2.5\text{ Hz})\} = \sum_{d > 100} \text{Ln}(d) \quad \sum_{m} P > 100\,(m,d)_2 \qquad \text{(Equation 7)}$$

where d is the centroid distance value for each distance bin.

When more than one earthquake magnitude-distance pair contributes significantly to the spectral accelerations at a given frequency, it may be necessary to use more than one controlling earthquake for determining the spectral response at the frequency.

Step 8

Document the high- and low-frequency controlling earthquakes for each target annual probability of exceedance in the tabular form illustrated in Table D.2.

Table D.2
High- and Low-Frequency Controlling Earthquakes

Hazard	Magnitude (m_b)	Distance
Mean 1 E-04 High-Frequency (5 and 10 Hz)		
Mean 1 E-04 Low-Frequency (1 and 2.5 Hz)		
Mean 1 E-05 High-Frequency (5 and 10 Hz)		
Mean 1 E-05 Low-Frequency (1 and 2.5 Hz)		
Mean 1 E-06 High-Frequency (5 and 10 Hz)		
Mean 1 E-06 Low-Frequency (1 and 2.5 Hz)		

Step 9

Develop response spectra using the controlling earthquake (high- and low-frequency) magnitudes and distances from Table D.2, and appropriate ground motion models. Scale these spectra to match the site rock spectral accelerations at 5 and 10 Hz (high-frequency) and 1 and 2.5 Hz (low-frequency).

D.3 Example for a Central and Eastern United States Site

To illustrate the procedure in Section D.2, calculations are shown here for a CEUS site. In this example, only the annual probability level of 1 E-05 is used.

It must be emphasized that the recommended magnitude and distance bins and procedure used to establish controlling earthquakes were developed for application in the CEUS, where the nearby earthquakes generally control the response in the 5 to 10 Hz frequency range, and larger but distant events can control the lower frequency range. For other situations, alternative binning schemes as well as a study of contributions from various bins will be necessary to identify controlling earthquakes consistent with the distribution of the seismicity.

Step 1

The PSHA used methods described in the 1993 LLNL seismic hazard methodology (Refs. D.2 and D.3). For this example, the databases and seismic sources identified in the LLNL or EPRI methodologies for CEUS sites (Refs. D.2–D.6) were evaluated to ensure that they contain up-to-date interpretations of earthquake sources, earthquake recurrence, and strong ground motion estimation. The analyses were performed for spectral acceleration at 1, 2.5, 5, and 10 Hz. The resultant hazard curves are plotted in Figure D.1.

Step 2

The hazard curves at 1, 2.5, 5, and 10 Hz obtained in Step 1 are assessed at the annual probability levels of 1 E-04, 1 E-05, and 1 E-06. As an example, the corresponding ground motion level values for the annual probability level of 1 E-05 are given in Table D.3. See Figure D.1.

The average of the ground motion levels at the 1 and 2.5 Hz, $S_{a1\text{-}2.5}$, and 5 and 10 Hz, $S_{a5\text{-}10}$, are given in Table D.4.

Table D.3
Ground Motion Levels

Frequency (Hz)	1	2.5	5	10
Spectral Acc. (cm/s/s)	88	258	351	551

Table D.4
Average Ground Motion Values

$S_{a\ 1\text{-}2.5}$ (cm/s/s)	173
$S_{a\ 5\text{-}10}$ (cm/s/s)	451

Step 3

The mean seismic hazard is deaggregated for the matrix of magnitude and distance bins as given in Table D.1.

The hazard values corresponding to the ground motion levels found in Step 2, and listed in Table D.3, are then determined from the hazard curve for each bin for spectral accelerations at 1, 2.5, 5, and 10 Hz. This process is illustrated in Figure D.2. The vertical line corresponds to the value 88 centimeter/second/second (cm/s/s) listed in Table D.3 for the 1 Hz hazard curve and intersects the hazard curve for the 25 - 50 bin, 6 - 6.5 bin, at a hazard value (probability of exceedance) of 2.14E-08/yr. Tables D.5 to D.8 list the appropriate hazard value for each bin for 1, 2.5, 5, and 10 Hz, respectively.

It should be noted that if the mean hazard in each of the 35 bins is added up, it should equal 1 E-05.

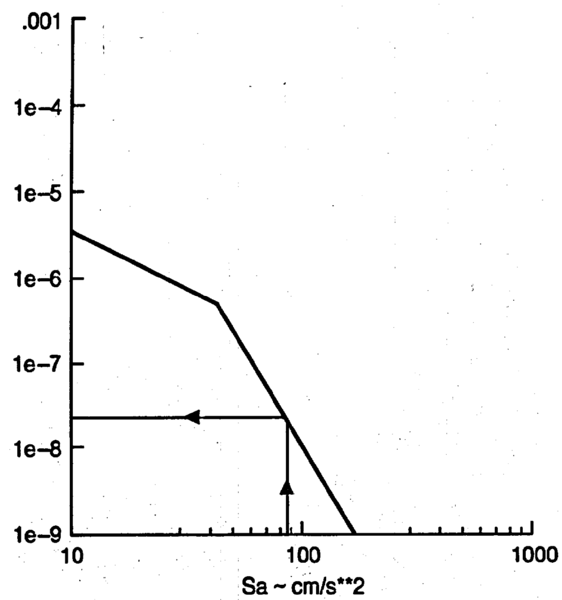

Figure D.2. 1 Hz Mean Hazard Curve for Distance Bin 25 - 50 km & Magnitude Bin 6 - 6.5

Table D.5
Mean Exceeding Probability Values for Spectral Accelerations at 1 Hz (88 cm/s/s)

Distance Range of Bin (km)	Magnitude Range of Bin				
	5 – 5.5	**5.5 – 6**	**6 – 6.5**	**6.5 – 7**	**>7**
0 – 15	1.90E-07	9.04E-07	1.09E-07	0	0
15 – 25	3.86E-08	2.47E-07	2.30E-08	0	0
25 – 50	1.65E-08	2.90E-07	2.05E-07	0	0
50 – 100	2.25E-09	1.47E-07	7.14E-07	2.40E-07	0
100 – 200	9.58E-11	2.26E-08	8.17E-07	5.84E-06	0
200 – 300	0	1.82E-10	1.53E-08	1.76E-07	0
> 300	0	0	8.61E-11	9.87E-11	1.62E-09

Table D6
Mean Exceeding Probability Values for Spectral Accelerations at 2.5 Hz (258 cm/s/s)

Distance Range of Bin (km)	Magnitude Range of Bin				
	5 – 5.5	**5.5 – 6**	**6 – 6.5**	**6.5 – 7**	**>7**
0 – 15	1.18E-06	1.76E-06	2.18E-07	0	0
15 – 25	2.85E-07	6.35E-07	5.71E-08	0	0
25 – 50	1.38E-07	8.89E-07	3.38E-07	0	0
50 – 100	2.07E-08	3.32E-07	7.72E-07	2.16E-07	0
100 – 200	7.94E-10	4.13E-08	5.66E-07	2.51E-06	0
200 – 300	3.79E-13	1.10E-10	3.95E-09	2.66E-08	0
> 300	0	8.04E-14	2.61E-12	4.79E-14	1.25E-14

Table D.7
Mean Exceeding Probability Values for Spectral Accelerations at 5 Hz (351 cm/s/s)

Distance Range of Bin (km)	Magnitude Range of Bin				
	5 – 5.5	**5.5 – 6**	**6 – 6.5**	**6.5 – 7**	**>7**
0 – 15	2.38E-06	2.81E-06	2.48E-07	0	0
15 – 25	4.51E-07	9.70E-07	6.53E-08	0	0
25 – 50	1.32E-07	8.83E-07	3.63E-07	0	0
50 – 100	5.90E-08	1.60E-07	4.79E-07	1.37E-07	0
100 – 200	3.87E-11	5.47E-09	1.22E-07	7.44E-07	0
200 – 300	0	1.15E-12	1.31E-10	1.93E-09	0
> 300	0	0	0	0	0

Table D.8
Mean Exceeding Probability Values for Spectral Accelerations at 10 Hz (551 cm/s/s)

Distance Range of Bin (km)	Magnitude Range of Bin				
	5 – 5.5	**5.5 – 6**	**6 – 6.5**	**6.5 – 7**	**>7**
0 – 15	3.19E-06	3.21E-06	2.38E-07	0	0
15 – 25	5.94E-07	1.08E-06	8.95E-08	0	0
25 – 50	1.18E-07	6.74E-07	2.96E-07	0	0
50 – 100	1.70E-09	6.60E-08	1.98E-07	7.78E-08	0
100 – 200	3.62E-12	4.85E-10	1.91E-08	1.56E-07	0
200 – 300	0	1.12E-14	1.77E-12	6.72E-11	0
> 300	0	0	0	0	0

Step 4

Using deaggregated mean hazard results, the fractional contribution of each magnitude-distance pair to the total hazard is determined.

Tables D.9 and D.10 show $P\,(m,d)_1$ and $P\,(m,d)_2$ for the average of 1 and 2.5 Hz and 5 and 10 Hz, respectively, using Equations 1 and 2.

Step 5

Because the contribution of the distance bins greater than 100 km in Table D.9 contains more than 5 percent of the total hazard for the average of 1 and 2.5 Hz, the controlling earthquake for the spectral average of 1 and 2.5 Hz is calculated using magnitude-distance bins for distance greater than 100 km. Table D.11 shows P > 100 $(m,d)_1$ for the average of 1 to 2.5 Hz, using Equation 3.

Table D.9
$P(m,d)_1$ for Average Spectral Accelerations 1 and 2.5 Hz
Corresponding to the 1 E-05 Annual Probability

Distance Range of Bin (km)	Magnitude Range of Bin				
	5 – 5.5	**5.5 – 6**	**6 – 6.5**	**6.5 – 7**	**>7**
0 – 15	0.069	0.133	0.016	0.000	0.000
15 – 25	0.016	0.044	0.004	0.000	0.000
25 – 50	0.008	0.059	0.027	0.000	0.000
50 – 100	0.001	0.024	0.074	0.023	0.000
100 – 200	0.000	0.003	0.069	0.418	0.000
200 – 300	0.000	0.000	0.001	0.010	0.000
> 300	0.000	0.000	0.000	0.000	0.000

Table D.10
$P(m,d)_2$ for Average Spectral Accelerations 5 and 10 Hz
Corresponding to the 1 E-05 Annual Probability

Distance Range of Bin (km)	Magnitude Range of Bin				
	5 – 5.5	**5.5 – 6**	**6 – 6.5**	**6.5 – 7**	**>7**
0 – 15	0.278	0.301	0.024	0.000	0.000
15 – 25	0.052	0.102	0.008	0.000	0.000
25 – 50	0.013	0.078	0.033	0.000	0.000
50 – 100	0.003	0.011	0.034	0.011	0.000
100 – 200	0.000	0.000	0.007	0.045	0.000
200 – 300	0.000	0.000	0.000	0.000	0.000
> 300	0.000	0.000	0.000	0.000	0.000

Table D.11
$P>100\ (m,d)_1$ for Average Spectral Accelerations 1 and 2.5 Hz
Corresponding to the 1 E-05 Annual Probability

Distance Range of Bin (km)	**Magnitude Range of Bin**				
	5 – 5.5	**5.5 – 6**	**6 – 6.5**	**6.5 – 7**	**>7**
100 – 200	0.000	0.006	0.138	0.833	0.000
200 – 300	0.000	0.000	0.002	0.020	0.000
> 300	0.000	0.000	0.000	0.000	0.000

Figures D.3 to D.5 show the above information in terms of the relative percentage contribution.

Steps 6 and 7

To compute the controlling magnitudes and distances at 1 to 2.5 Hz and 5 to 10 Hz for the example site, the values of $P > 100\ (m,d)_1$ and $P\ (m,d)_2$ are used with m and d values corresponding to the mid-point of the magnitude of the bin (5.25, 5.75, 6.25, 6.75, 7.3) and centroid of the ring area (10, 20.4, 38.9, 77.8, 155.6, 253.3, and somewhat arbitrarily 350 km). Note that the mid-point of the last magnitude bin may change because this value is dependent on the maximum magnitudes used in the hazard analysis.

Step 8

The high- and low-frequency controlling earthquakes for all frequency levels are shown in Table D.12. Provide a description of the source of each high- and low-frequency controlling earthquake.

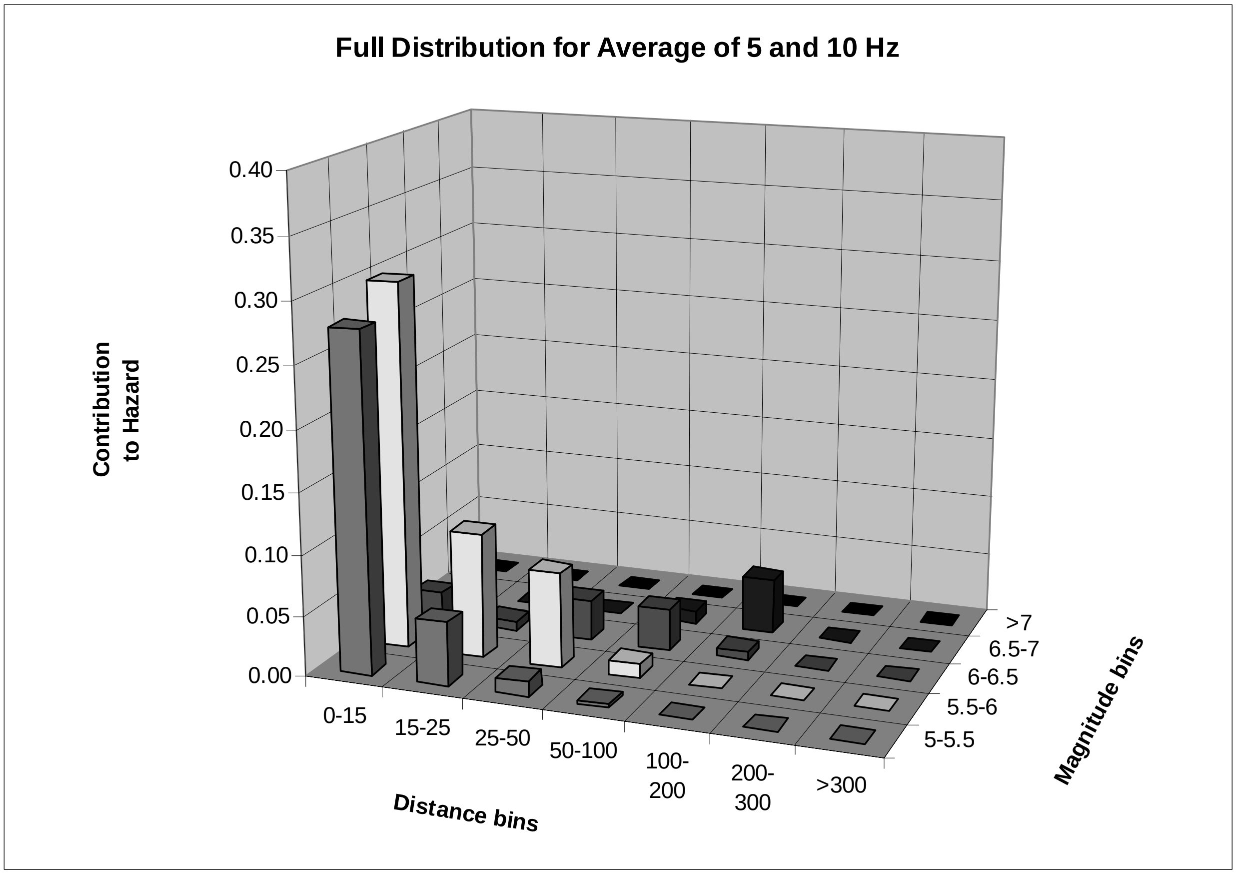

Figure D.3. Full Distribution for Average of 5 and 10 Hz

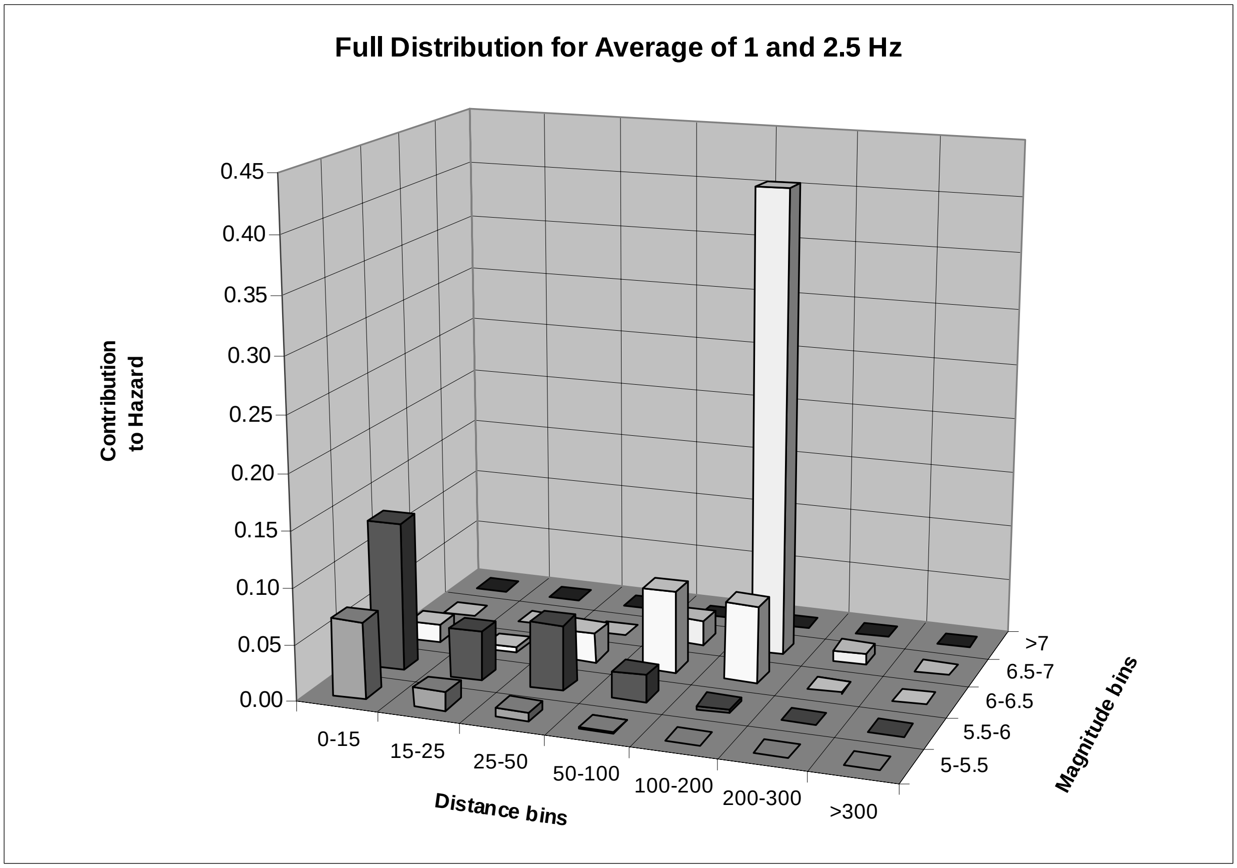

Figure D.4. Full Distribution for Average of 1 and 2.5 Hz

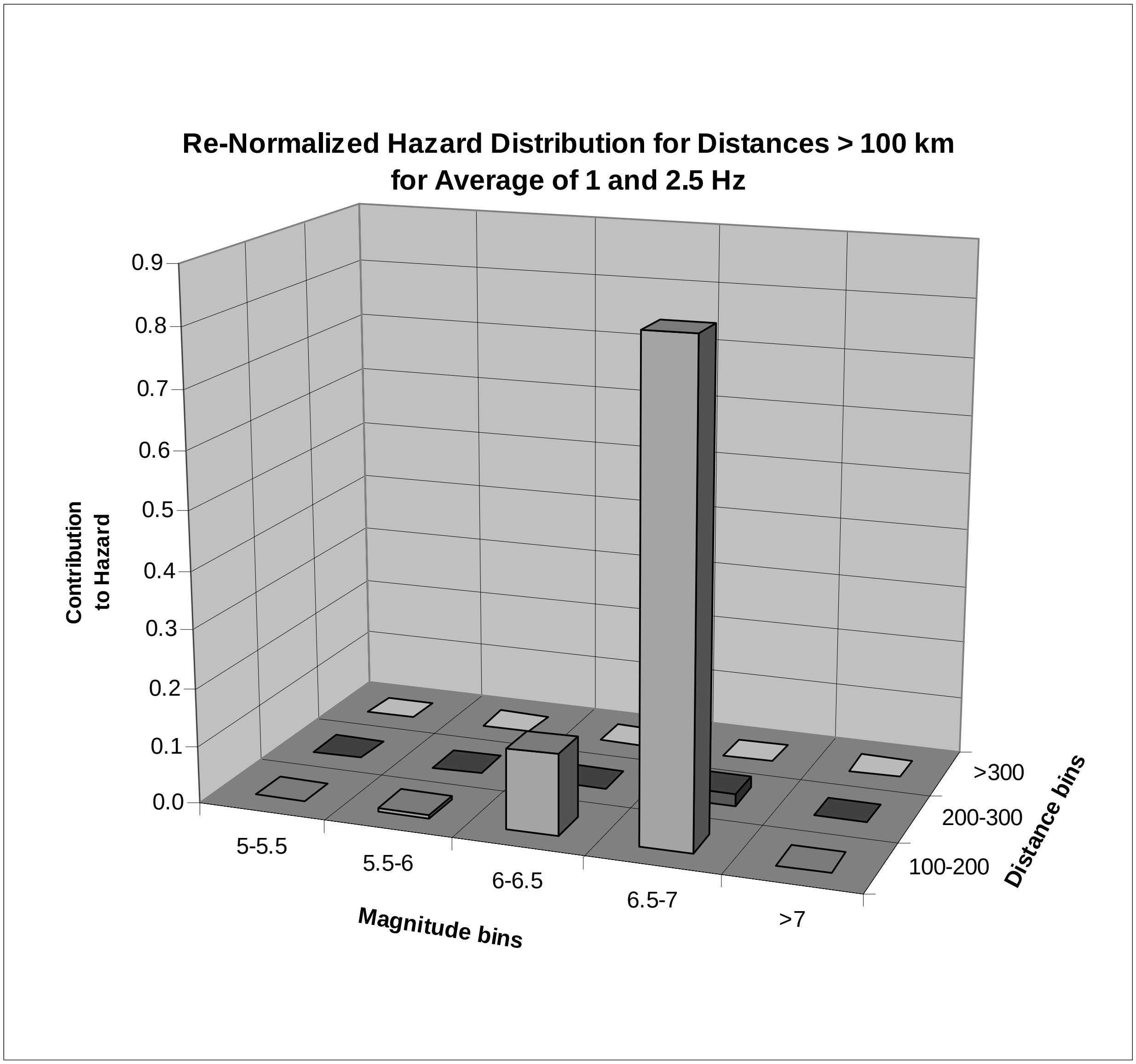

Figure D.5. Renormalized Hazard Distribution for Distances > 100 km for Average of 1 and 2.5 Hz

Table D.12
Magnitude and Distances
of High- and Low-Frequency Controlling Earthquakes
from the LLNL Probabilistic Analysis

Hazard	Magnitude (m_b)	Distance
Mean 1 E-04 **High-Frequency (5 and 10 Hz)**	From Steps 2 – 7	
Mean 1 E-04 **Low-Frequency (1 and 2.5 Hz)**		
Mean 1 E-05 **High-Frequency (5 and 10 Hz)**	5.7	17 km (10 mi)
Mean 1 E-05 **Low-Frequency (1 and 2.5 Hz)**	6.7	157 km (97 mi)
Mean 1 E-06 **High-Frequency (5 and 10 Hz)**	From steps 2 – 7	
Mean 1 E-06 **Low-Frequency (1 and 2.5 Hz)**		

Step 9

The response spectra used for the site response analysis is obtained using the controlling earthquake (high- and low-frequency) magnitudes and distances in Table D.12, using appropriate ground motion models (e.g., the EPRI ground motions models in Reference D.7 for the CEUS), and then scaling these spectra to match the site rock spectral accelerations at 5 and 10 Hz (high-frequency) and 1 and 2.5 Hz (low-frequency).

D.4 Sites Not in the Central and Eastern United States

The determination of the controlling earthquakes and the seismic hazard information base for sites not in the CEUS is also carried out using the procedure described in Section D.2 of this appendix. However, because of differences in seismicity rates and ground motion attenuation at these sites, alternative magnitude-distance bins may have to be used.

APPENDIX D REFERENCES

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2 Copies are available for inspection or copying for a fee from the NRC’s Public Document Room at 11555 Rockville Pike, Rockville, MD; the PDR’s mailing address is USNRC PDR, Washington, DC 20555; telephone (301) 415-4737 or (800) 397-4209; fax (301) 415-3548; email PDR@nrc.gov. In addition, copies are available at current rates from the U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20402-9328, telephone (202) 512-1800; or from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161, http://www.ntis.gov, telephone (703) 487-4650.

APPENDIX E

SEISMIC WAVE TRANSMISSION ANALYSIS

E.1 Introduction

This appendix elaborates on the procedure described in Regulatory Position 4 of this regulatory guide to develop the uniform hazard response spectrum (UHRS) at the free-field ground surface. The hazard curves from the probabilistic seismic hazard analysis (PSHA) are defined for generic hard rock conditions usually with a shear wave velocity (V_s) about 2.8 km/sec (9200 ft/sec). To properly address amplification or deamplification effects of the soils between the generic hard rock and the ground surface and other interfaces in between, the following procedure should be used:

(1) Develop the site-specific soil profile.

(2) Develop appropriate modified earthquake time histories to be used in site response analyses.

(3) Perform a suite of site response analyses to determine mean site amplification functions for a range of frequencies.

(4) Develop the UHRS at the free ground surface based on the generic rock-based PSHA and the mean site amplification functions.

The horizontal and vertical safe shutdown earthquake ground motion (SSE) should be determined in the free field on the ground surface. For sites with V_s less than the assumed hard-rock shear wave velocity, as defined in the PSHA, a site response analysis should be performed. The input ground motion used in the analyses are specified based on the PSHA, which assumes that an outcrop or a hypothetical outcrop exists at the free-field surface. If the rock layer (as defined by shear wave velocity) first occurs at depth, the input ground motions are deconvolved to develop "within" motions and imposed at the highest layer of the generic hard rock [greater than 2.8 km/sec (9200 ft/sec)].

E.2 Site-Specific Soil Profile

Site and laboratory investigations and testing are performed to obtain data defining the static and dynamic engineering properties of soil and rock materials, and their spatial distribution. The procedures identified in Regulatory Guide 1.132 (Ref. E.1), Regulatory Guide 1.138 (Ref. E.2), and subsection C.2.2.2 of Appendix C to this regulatory guide are acceptable to the NRC staff.

To be acceptable, the seismic wave transmission characteristics (spectral amplification or deamplification) of the materials overlying bedrock at the site are described over a range of frequencies that include the significant structural frequencies. The wave transmission characteristics should be developed for levels of seismic motion ranging from those causing very small strains (i.e., no soil degradation) to those consistent with strain levels anticipated in the SSE. The following material properties should be determined for each stratum under the site: (1) thickness, (2) compressional velocity, (3) shear wave velocity, (4) bulk densities, (5) soil index properties and classification, (6) shear modulus and damping variations with strain level, and (7) the water table elevation and its variation throughout the site. Site specific soil profiles should be deep enough to fully capture the amplification to the lowest structural frequency of interest and should extend to the depth at which the input ground motion is to be imposed [typically the depth at which V_s = 2.8 km/sec (9200 ft/sec)].

Often vertically propagating shear waves are the dominant contributor to free-field ground motions at a site. In these cases, a one-dimensional equivalent-linear analysis or nonlinear analysis that assumes vertical propagation of shear waves may be appropriate. However, site characteristics (such as a dipping bedrock surface or other impedance boundaries), regional characteristics (such as topographic effects), and source characteristics (such as nearby dipping seismic sources) may require that analyses be able to also account for inclined waves.

E.3 Site Response Analysis

To estimate site response, input ground motions are needed for the analyses performed. The choice of input ground motions have significant impact on the amplification of motion observed in the soil column. A range of key earthquake scenarios, known as the controlling earthquakes, are developed to focus the analyses on the types of scenarios most likely to impact the site.

To develop these controlling earthquakes and to better understand how different sources within a seismic source model contribute to the overall seismic hazard, the seismic hazard developed by the PSHA is deaggregated into a series of magnitude-distance bins for a variety of spectral frequencies and annual exceedance frequencies. Based on the results of the deaggregation, the earthquake scenarios that most contribute to the high-frequency (5 and 10Hz) and low-frequency (1 and 2.5 Hz) spectral motions with annual exceedance frequencies of 1 E-04, 1 E-05 and 1 E-06 are determined. The distance-magnitude bins from the 5 and 10 Hz frequencies are averaged, and the 1 and 2.5 Hz frequencies are averaged, and the controlling earthquakes (dominant distance and magnitude bin) is determined for the high- and low-frequency motions for each of the 3 annual frequencies.

The response spectra for each of the six individual controlling earthquakes determined above are developed using appropriate attenuation relationships. The resulting response spectra are then scaled to match the site rock spectral accelerations at either 5 and 10 Hz (high-frequency) or at 1 and 2.5 Hz (low-frequency).

Once the spectra for each controlling earthquake are determined and scaled, the spectra are plotted and compared against the natural frequency of the soil to assure that the spectra from at least one key earthquake scenario have sufficient energy content at the natural frequency of the site as determined by the full rock-based UHRS. A visual comparison of the spectra from the controlling earthquakes, the UHRS spectra, and the natural frequency of the soil column should be provided. For sites with numerous contributing earthquakes, or if the natural frequency of the site is not adequately covered by the use of six controlling earthquakes, more complex methodologies should be applied.

After determining the scaled response spectra from each of the characteristic earthquakes, corresponding acceleration time histories are identified and their spectra compared to the target characteristic earthquakes spectra. The acceleration time histories are modified to match the target spectra. The scaled time histories are imposed in the developed subsurface model (as equivalent “within” motions) at the bedrock level. The imposed motions propagate through the analytical model of the site soils to determine the free-field surface ground motions (Regulatory Position 4.2). Only acceleration time histories modified from recorded earthquakes are used for this purpose.

The required soil parameters for the site response analyses include the depth, soil type, density, shear wave velocity, shear modulus and damping, and their variations with strain levels for each of the soil layers. Internal friction angle, cohesive strength, and over-consolidation ratio for clay are also needed for non-linear analyses. The strain-dependent shear modulus and damping curves are developed based on site-specific testing results and supplemented as appropriate by published data for similar soils.

The strain-dependent shear modulus and damping curves incorporated into the analysis should be justified against observed data for each soil at the site. When site-specific laboratory data is used, the result should be compared to earthquake recordings on similar soils. A maximum critical damping value of 15 percent is allowed in site response analyses. The effects of confining pressures (that reflect the depths of the soil) on these strain-dependent soil dynamic characteristics are assessed and considered in site response analyses. The variability in these properties is accounted for in the site response analyses. Steeply dipping soil layers or other contrasting impedance interfaces, such as fault zones or valley walls, should also be considered because the existence of those interfaces will influence the wave propagation from the reference hard rock to the ground surface. Multi dimensional soil models may be needed if complex geologic and geotechnical conditions exist.

As a minimum, the results of the site response analysis should show the input motion (rock response spectra), output motion (surface response spectra), and spectral amplification function (site ground motion transfer function) at the surface. It is common practice to also provide a plot showing the peak accelerations in the soil as a function of depth. In addition to developing the spectral amplifications functions at the surface, it is also useful to simultaneously develop the spectral amplification functions for the foundation level for use in development of the SSE. However, because the location of the foundation is not always known at the time at which the analyses are undertaken, the functions may be determined at several depths including the deepest depth from the Plant Parameter Envelope. In addition, determining and providing the spectral amplification functions at a variety of depths may support review of the results used in determining the soil UHRS and the SSE.

To determine the UHRS at the free-field ground surface, the site amplification functions (spectral ratios) for each characteristic earthquake scenario are computed. To capture the variation of the soil properties at the site, it usually requires that 60 randomized shear velocity profiles are paired with 60 sets of randomized shear modulus and damping curves (i.e., one shear velocity profile with one set of modulus reduction and damping curves). The mean site amplification function is obtained for each characteristic earthquake scenario by dividing the response spectrum from the computed surface motion by the response spectrum from the input hard-rock surface motion, and computing the arithmetic mean of these 60 individual response spectral ratios.

Figure E.1 compares the 1 E-05 rock UHRS, the target spectra for the high- and low-frequency controlling earthquakes, and the natural frequency of the soil column at the site.

Figure E.2 shows the computed high- and low-frequency average site amplification functions for the mean 1 E-05 hazard level characteristic earthquake scenarios. As shown in Figure E.2, the soil column amplifies the input hard rock motion over the fairly wide frequency range. The lines shown in Figure E.2 are the final average site amplification function for each controlling earthquake based on a suite of site response analyses that take into account uncertainty in the soil model and use a variety of appropriate time histories.

Once the soil amplification functions are developed, they are applied to the free-field rock UHRS to develop two free-field soil spectra. To determine the soil UHRS at the free-field ground surface, for each of the annual exceedance frequencies (1 E-04, 1 E-05 and 1 E-06), multiply the rock-based UHRS at all 25 points and the natural frequency of the site soil column by the site amplification functions, and envelop the results. These two curves are enveloped to determine the final free-field soil UHRS. If the two controlling earthquake response spectral shapes cover a broad range of frequencies such that when scaled and enveloped they approximate the UHRS, then it is also acceptable to multiply the high- and low-frequency controlling earthquake spectra by the appropriate site amplification function and envelope the results. Figure E.3 shows a comparison of the results when each of the soil amplification functions are applied to the free-field rock UHRS and the final free-field soil UHRS.

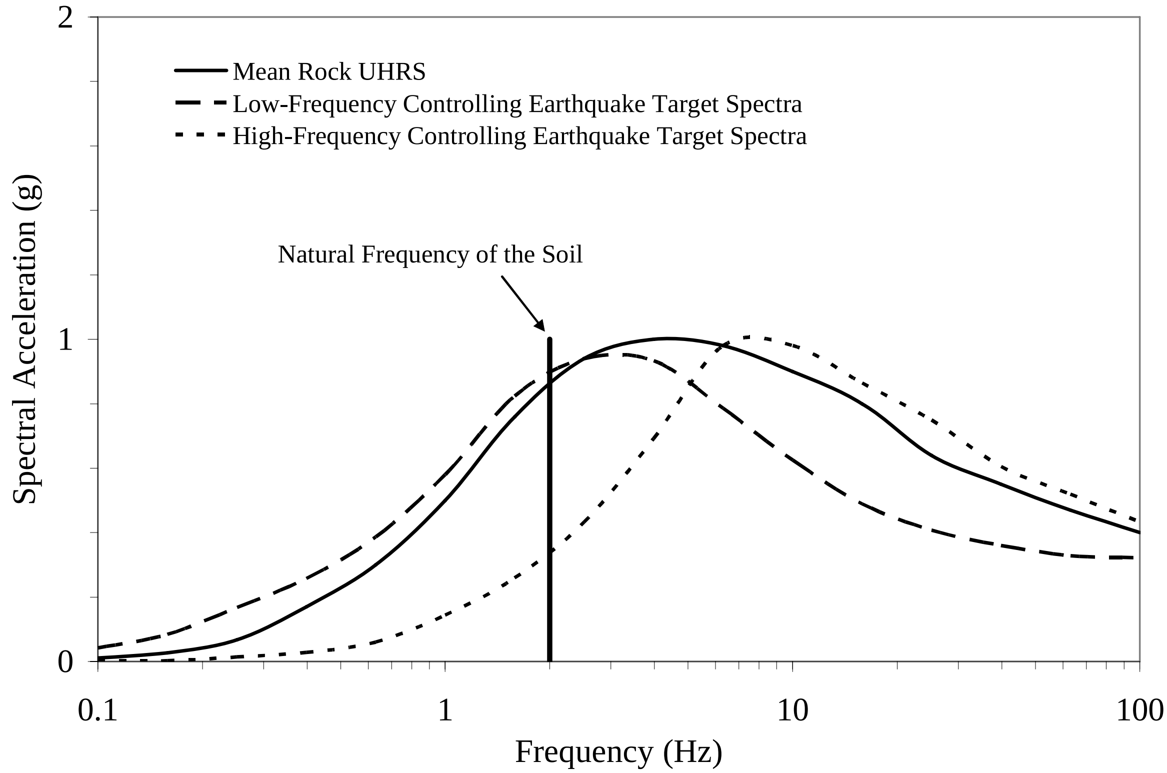

Figure E.1. Comparison of the 1 E-05 Rock UHRS, the Target Spectra for the High- and Low-Frequency Controlling Earthquakes, and the Natural Frequency of the Soil Column

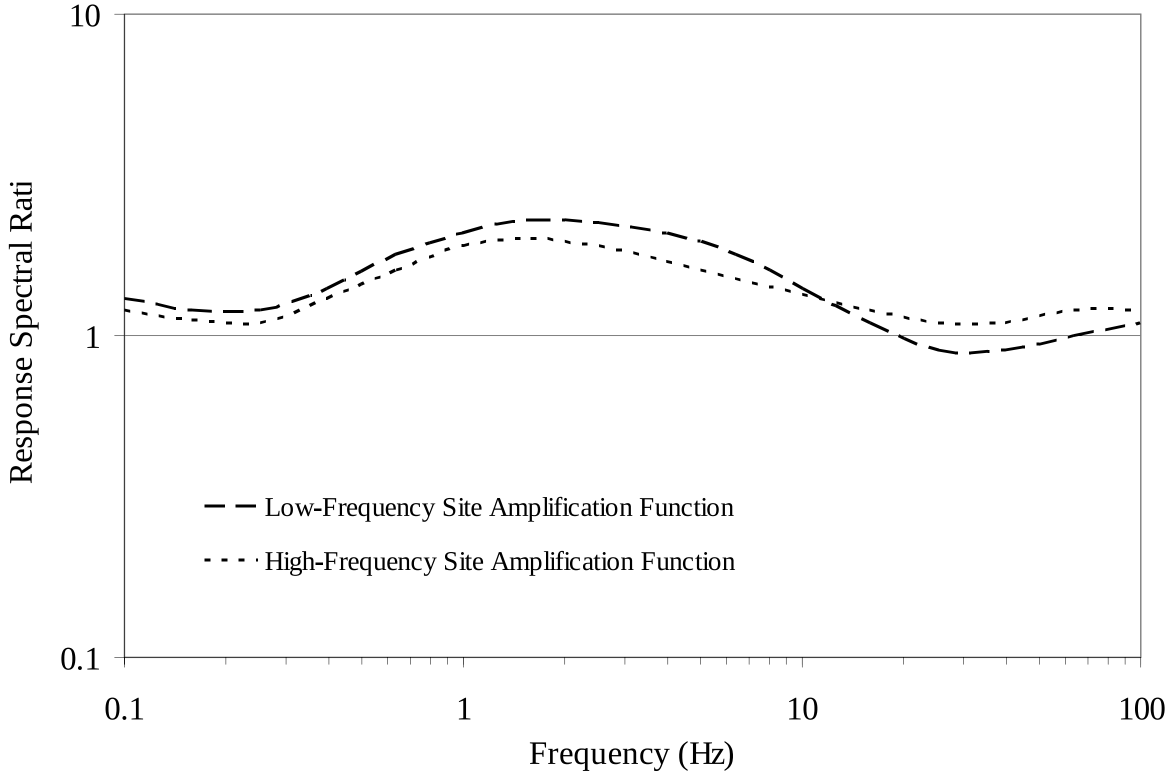

Figure E.2. Mean Site Amplification Functions for Low- and High-Frequency Characteristic Earthquakes for 1 E-05 Annual Probability Level

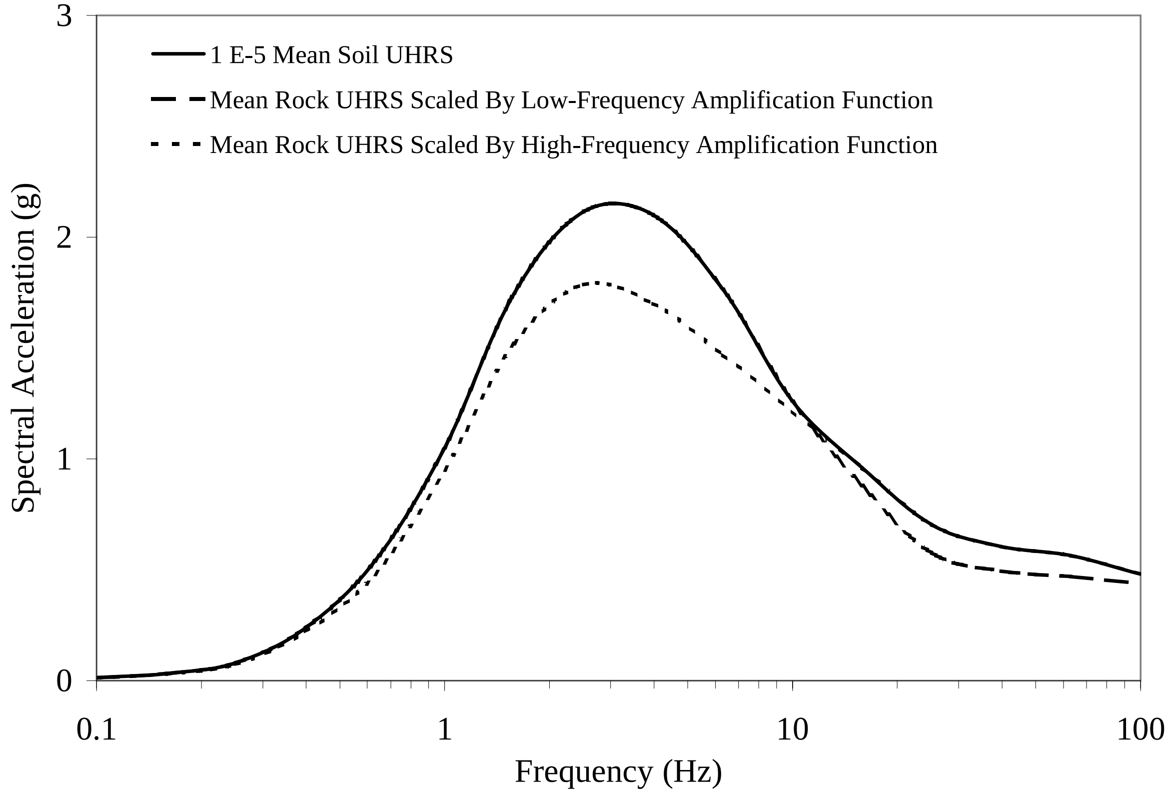

Figure E.3. Free-Surface Soil Uniform Hazard Response Spectra Compared to Spectra Resulting from Scaling of Mean Rock UHRS by Low- and High-Frequency Amplification Functions

E.4 Free-Field Ground Surface Uniform Hazard Response Spectra

In accordance with Regulatory Position 4.3 of this regulatory guide, the UHRS at the free-field ground surface is determined for the site by first scaling the appropriate UHRS at the rock surface by the mean site amplification functions developed for both the low- and high-frequency ranges and then enveloping both sets of results by a smooth curve. These smooth UHRS are used in Regulatory Position 5 of this regulatory guide to develop the performance-based horizontal and vertical response spectra.

APPENDIX E REFERENCES

E.1 **Regulatory Guide 1.132**, "Site Investigations for Foundations of Nuclear Power Plants," Revision 1, U.S. Nuclear Regulatory Commission, Washington, DC, October 2003, available in ADAMS under Accession #ML032800710.[1]

E.2 **Regulatory Guide 1.138**, "Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants," Revision 2, U.S. Nuclear Regulatory Commission, Washington, DC, December 2003 available in ADAMS under Accession #ML003740184.[1]

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[1] All regulatory guides listed herein were published by the U.S. Nuclear Regulatory Commission. Where an ADAMS accession number is identified, the specified regulatory guide is available electronically through the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html. All other regulatory guides are available electronically through the Public Electronic Reading Room on the NRC's public Web site, at http://www.nrc.gov/reading-rm/doc-collections/reg-guides/. Single copies of regulatory guides may also be obtained free of charge by writing the Reproduction and Distribution Services Section, ADM, USNRC, Washington, DC 20555-0001, or by fax to (301) 415-2289, or by email to DISTRIBUTION@nrc.gov. Active guides may also be purchased from the National Technical Information Service (NTIS) on a standing order basis. Details on this service may be obtained by contacting NTIS at 5285 Port Royal Road, Springfield, Virginia 22161, online at http://www.ntis.gov, or by telephone at (703) 487-4650. Copies are also available for inspection or copying for a fee from the NRC's Public Document Room (PDR), which is located at 11555 Rockville Pike, Rockville, Maryland; the PDR's mailing address is USNRC PDR, Washington, DC 20555-0001. The PDR can also be reached by telephone at (301) 415-4737 or (800) 397-4205, by fax at (301) 415-3548, and by email to PDR@nrc.gov.

APPENDIX F

CRITERIA FOR DEVELOPING TIME HISTORIES

This appendix provides criteria for developing and evaluating modified ground motions used for soil response and structural analyses. Recorded or modified recorded earthquake ground motion time histories may be used for linear seismic analysis. Actual recorded earthquake ground motion or modified recorded ground motions should be used for nonlinear seismic analysis.

The general objective is to generate a modified recorded accelerogram that achieves approximately a mean-based fit to the target spectrum. That is, the average ratio of the spectral acceleration calculated from the accelerogram to the target, where the ratio is calculated frequency by frequency, is only slightly greater than one. The aim is to achieve an accelerogram that does not have significant gaps in the Fourier amplitude spectrum, but which is not biased high with respect to the target. Time histories biased high with respect to a spectral target may overdrive (overestimate damping and stiffness reduction) a site soil column or structure when nonlinear effects are important. Ground motions that are generated to "match" or "envelop" given design response spectral shapes should comply with the following six steps:

(1) The time history should have a sufficiently small time increment and sufficiently long durations. Time histories should have a Nyquist frequency of at least 50 Hz (e.g., a time increment of at most 0.010 seconds) and a total duration of 20 seconds. If frequencies higher than 50 Hz are of interest, the time increment of the record must be suitably reduced to provide a Nyquist frequency ($N_y = 1/(2\ \Delta_t)$, where Δ_t = time increment) above the maximum frequency of interest. The total duration of the record can be increased by zero packing to satisfy these frequency criteria.

(2) Spectral accelerations at 5 percent damping are computed at a minimum of 100 points per frequency decade, uniformly spaced over the log frequency scale from 0.1 Hz to 50 Hz or the Nyquist frequency. If the target response spectrum is defined in the frequency range from 0.2 Hz to 25 Hz, the comparison of the modified motion response spectrum with the target spectrum is made at each frequency computed in this frequency range.

(3) The computed 5 percent damped response spectrum of the average of all accelerograms should not fall more than 10 percent below the target spectrum at any one frequency. To prevent spectra in large frequency windows from falling below the target spectrum, the spectra within a frequency window of no larger than ± 10 percent centered on the frequency should be allowed to fall below the target spectrum. This corresponds to spectra at no more than nine adjacent frequency points defined in (2) above from falling below the target spectrum.

(4) The mean of the 5 percent damped response spectra should not exceed the target spectrum at any frequency by more than 30 percent (a factor of 1.3) in the frequency range between 0.2 Hz and 25 Hz. If the spectrum for the accelerogram exceeds the target spectrum by more than 30 percent at any frequency in this frequency range, the power spectral density of the accelerogram needs to be computed and shown to not have significant gaps in energy at any frequency over the frequency range.

(5) Because of the high variability in time domain characteristics of recorded earthquakes of similar magnitudes and at similar distances, strict time domain criteria are not recommended. However, modified motions defined as described above should typically have durations (defined by the 5 percent to 75 percent Arias intensity), and ratios V/A and AD/V^2 (A, V, and D are peak ground acceleration, ground velocity, and ground displacement, respectively), which are generally consistent with characteristic values for the magnitude and distance of the appropriate controlling events defining the uniform hazard response spectra. However, in some tectonic settings these criteria may need to be altered to accommodate phenomena, such as, directivity, basin effects, and hanging wall effects.

(6) To be considered statistically independent, the directional correlation coefficients between pairs of time histories should not exceed a value of 0.30[1]. Simply shifting the starting time of a given accelerogram does not constitute the establishment of a different accelerogram.

[1] The directional correlation coefficient is a measure of the degree of linear relationship between two earthquake accelerograms. For accelerograms X and Y, the directional correlation coefficient is given by the following equation:

$$\rho_{xy} = \{ (1/n) (\sum_{i=1}^{n} [(X_i - \bar{x}) (Y_i - \bar{y})]) \} \div \{ \sigma_x \sigma_y \}$$

where n is the number of discrete acceleration-time data points, $\bar{x}$ and $\bar{y}$ are the mean values, and σ_x and σ_y are the standard deviations of X and Y, respectively.