Development of a Performance-Based Approach to Seismic Siting and Design

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ABSTRACT

In 1996 and 1997, the U.S. Nuclear Regulatory Commission (NRC) published a new Title 10, Section 100.23, "Geologic and Seismic Siting Criteria," of the *Code of Federal Regulations* (10 CFR 100.23) and a series of supporting regulatory guides. Regulatory Guide 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion," issued March 1997 [1], is one of this series and contains the basic guidance for the development of the safe-shutdown earthquake (SSE) ground motion response spectra (GMRS), which is the characterization of seismic loading that governs the seismic design of nuclear power plants (NPPs). This guidance was effectively untested until three utilities applied for early site permits in 2003. In the same timeframe, the Electric Power Research Institute (EPRI) completed a comprehensive new study of the attenuation of seismic ground motion for the central and eastern United States [2]. Using this updated ground motion attenuation model in the EPRI probabilistic seismic hazard assessment (PSHA) methodology, in a number of cases, site-specific GMRS exceed the seismic response spectra used in the certification of new NPP designs. These exceedances are in the high-frequency portion of the response spectra and might or might not represent challenges to the facility.

To address the issue of these exceedances, the Nuclear Energy Institute (NEI), acting for the U.S. nuclear industry, proposed a revision of the regulatory guidance based on a risk-informed, performance-based approach described in the American Society of Civil Engineers (ASCE) and Structural Engineering Institute (SEI) standard ASCE/SEI 43-05, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities" [3], finalized in July 2005. In addition to proposing to change the basis of the regulatory guide to a risk-consistent approach, NEI has proposed several changes to the PSHA methodology. This paper describes the risk-informed, performance-based approach and technical basis of the ASCE/SEI 43-05 standard, associated regulatory issues, and details of proposed changes to the PSHA methodology. Based in part on ASCE/SEI 43-05, the NRC staff published a draft of a new regulatory guide for public comment in December 2006 and issued the final version, Regulatory Guide 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion" [4], in March 2007.

BACKGROUND OF CURRENT SITING RULES AND STANDARDS

This section describes the technical materials used in developing the new risk-informed and performance-based regulatory guidance for seismic siting of NPPs in the United States. These materials include NRC regulation and regulatory guidance, U.S. Department of Energy (DOE) seismic standards, and industry consensus standards. The new NRC Regulatory Guide 1.208 is an alternative to existing Regulatory Guide 1.165, which was available for the four early site permit applications (Clinton, North Anna, Grand Gulf, and Vogtle) under various stages of NRC review in spring 2007. (As of April 2007, Clinton and Grand Gulf have received early site permits.) Regulatory Guide 1.165 will remain an acceptable alternative to Regulatory Guide 1.208 for determining the SSE GMRS.

10 CFR 100.23 and Regulatory Guide 1.165

After many years (1973 through 1997) of experience with Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants," to 10 CFR Part 100, "Reactor Site Criteria," the NRC acknowledged both the successful use of this regulation and the technical and adjudicatory difficulties in its implementation. These observations led to its replacement with the shortened, streamlined rule in 10 CFR 100.23. This new rule accomplished a number of very important changes, specifically (1) removing the prescriptive guidance in the rule itself and moving the guidance to the standalone Regulatory Guide 1.165, (2) acknowledging the uncertainty in the seismic/geologic knowledge base and requiring that the uncertainties be estimated through an appropriate analysis, and (3) explicitly accepting the use of PSHA to satisfy this uncertainty requirement.

Regulatory Guide 1.165, issued March 1997, contains guidance on developing the SSE ground motion, which is characterized by a site response spectrum. Regulatory Guide 1.165 contains (1) guidance on the geological and seismological investigations that should be conducted to fully characterize the NPP site and its environs, (2) guidance on acceptable PSHA databases and methodologies, explicitly naming both the Lawrence Livermore National Laboratory (LLNL) [5] and EPRI [6] methods as acceptable, (3) a description of a reference probability that provides uniformity of seismic hazard exposure between operating NPPs and future NPPs (using a reference probability of exceedance set to a median annual value of $1x10^{-5}$), (4) a description of the determination of the reference probability and its use in obtaining the SSE, and (5) guidance on ensuring that the PSHA databases are current.

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Regulatory Guide 1.60

Revision 1 of Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants," issued December 1973 [7], is the companion regulatory guidance for Appendix A to 10 CFR Part 100 for determining the seismic design response spectra from the SSE spectra. In 1997, the NRC staff initiated research to develop a technical basis for the revision and update of the guidance to build on the development of PSHA guidance in Regulatory Guide 1.165. Two NUREG/CR reports [8, 9] document this research. These two reports are pivotal in providing a technical basis for the development of risk-consistent seismic spectra through the modification of uniform hazard response spectra (UHRS) by considering the site-specific slope of the hazard curves. The research also examined available methods for modifying the UHRS for site-specific soil conditions, including evaluating and characterizing four methods based on their approach. The four methods were demonstrated for two sites, one in California and one in South Carolina, and the results were discussed, including noting the advantages and issues associated with each. The research also developed a database of strong ground motion recordings characterized by magnitude and distance, from source to recorder, for potential use in a revised regulatory guide on design response spectra.

Department of Energy Standard 1020

In 2002, DOE published a revision to its seismic siting standard, "Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities" [10]. It states, "This natural phenomena hazard standard...provides criteria for design of new SSCs (structures, systems and components) and for evaluation, modification, or upgrade of existing SSCs so that DOE facilities safely withstand the effects of natural phenomena hazards, such as earthquakes, extreme winds, and flooding." The NRC staff was interested in the performance-based approach that DOE applied to the issue of seismic siting and that ASCE/SEI adopted in its standard. The DOE standard expressed this approach by stating, "[T]he intent is to control the level of conservatism in the design/evaluation process such that (1) the hazards are treated consistently; and (2) the level of conservatism is appropriate for SSC characteristics related to safety, environmental protection, importance, and cost." Although the ASCE/SEI standard discussed in the following section only addressed seismic hazards, it followed the DOE approach of addressing seismic hazards consistently through a performance goal for facility characteristics across the entire country.

ASCE/SEI 43-05

In July 2005, ASCE/SEI published a standard for the seismic design of safety-related structures, systems, and components (SSCs) in a broad spectrum of nuclear facilities, but did not specifically address commercial NPPs. This standard was developed for DOE and its nuclear facilities. In view of the current trend in both the conventional and nuclear design and construction industries toward using risk-informed and performance-based methods in various consensus codes and standards, ASCE/SEI decided to move in this direction as well. The resultant standard is ASCE/SEI 43-05. Without specifically addressing commercial NPPs, the standard contains a number of technical concepts that could be useful in design guidance for commercial NPPs. Two of the most important and useful elements are (1) the development of a technical basis for a performance-based approach to determination of a site-specific SSE GMRS and (2) a technical basis for a target performance goal.

In addition, a third prime element used in the standard is the frequency of the onset of significant inelastic deformation (FOSID). (Although ASCE/SEI does not refer to this concept by the acronym FOSID, the technical community frequently uses this acronym.) ASCE/SEI is making use of this concept instead of the previous criterion, seismic core damage frequency (SCDF), which has been the term of reference in seismic probabilistic risk assessments or probabilistic safety assessments. FOSID as a limit state ensures that, although NPP SSCs might have localized inelastic response, they will remain essentially within elastic limits globally. In contrast, the seismic core damage limit state occurs when there are plant system and component failures. NEI has performed SCDF analysis based on seismic hazard and idealized fragility functions for 28 sites and established that the FOSID performance target is conservative, such that the seismic hazard based on the FOSID performance target would limit the SCDF to less than 5×10^{-6} per year.

PUBLIC INTERACTIONS DURING DEVELOPMENT OF NEW REGULATORY GUIDE

As required by law and as a matter of good procedure and practice, the NRC initiates interactions with the public during the development of its regulations and regulatory guidance. (One of the NRC's strategic goals is to ensure openness in its regulatory process.) The NRC commonly uses two mechanisms to obtain public input to inform the process, specifically public meetings and public comment periods, both of which the agency announces formally through the *Federal Register*, during which draft copies of the material are available. In a series of public meetings, the NRC staff interacted extensively with interested stakeholders during the development of the subject regulatory guidance.

Nuclear Energy Institute Activities

As the U.S. nuclear power generating industry moved toward a resurgence in the development of new generating capacity, NEI, representing the nuclear industry as a whole, undertook the task of identifying and resolving regulatory issues potentially affecting the efficient licensing of new NPPs. While acknowledging the strong points of the current guidance and its up-to-date elements, NEI identified two issues that potentially could impede the goal of efficient licensing. First, the current guidance does not take into specific consideration the advances that have been made in modeling ground motion propagation in the central and eastern United States since Regulatory Guide 1.165 used the EPRI and LLNL PSHA methods and databases in 1997. Second, the current guidance does not make use of the development of risk-informed, performance-based procedures for the determination of site-specific SSE response spectra.

NEI undertook its New Plant Seismic Issues Resolution Program to develop technical information to specifically inform the NRC process for developing the subject regulatory guidance. NEI provided this information in a series of reports to the NRC that are publically available on the NRC Web site [11].

NEI drafted an integration report [12] that included a series of recommendations for the industry that it proposed for incorporation in the new seismic siting guidance. These recommendations include guidance on the following:

1) generic updating of earthquake recurrence and ground motion elements
   - 1a) implementation of the cumulative absolute velocity (CAV) filter
   - 1b) implementation of the EPRI ground motion model [2]
2) implementation of the ASCE/SEI 43-05 standard to determine the SSE response spectra
3) determination of the response of local site geology to seismic waves
4) determination of site-specific, risk-informed seismic design response spectra
5) determination of the control point location for the site-specific safe-shutdown response spectra and the seismic design response spectra

Basis for Performance-Based Approach and Target Performance Goal

NEI noted that the NRC expressed its desire in two documents [13, 14] to move specifically to the use of risk-informed and performance-based principles in new regulations and regulatory guidance. Building on this NRC commitment to employ these regulatory principles, NEI advocated the use of ASCE/SEI 43-05 as the basis for a performance-based regulatory guide with a specific mean annual target probability goal of $1x10^{-5}$. Through a series of presentations and tutorials at public meetings, NEI and its consultants provided technical material to justify the use of the ASCE/SEI 43-05 approach and the target probability [11].

Cumulative Absolute Velocity Filter

With the introduction of recent ground motion attenuation models for the central and eastern United States into modern PSHA, there has been a tendency toward an increasing level of ground motion, particularly in the high-frequency end of the response spectrum, as noted by EPRI [15]. EPRI attributed a significant portion of this observed increase to the influence of small-magnitude earthquakes in the PSHAs. Earlier research has shown that small-magnitude earthquakes are not damaging to well-engineered structures such as those in NPPs. NEI has proposed using a CAV value of 0.16 g-sec as a filter level to remove the effect of small-magnitude earthquakes from a PSHA. O'Hara and Jacobson [16] have demonstrated that a CAV value of 0.16 g-sec represents a level of ground motion observed to be nondamaging to buildings of good design and construction. This is the same value that the NRC used in Regulatory Guide 1.166, "Pre-Earthquake Planning and Immediate Nuclear Power Plant Operator Postearthquake Actions," issued March 1997 [17], to determine whether the NPP has experienced an operating-basis earthquake.

Public Meetings

Between May 2005 and September 2006, the NRC conducted seven public meetings, several spanning 2 days each, to collect technical information. The NRC staff used this information to inform the preparation of the new regulatory guide on the determination of site-specific seismic hazards. The NRC anticipates additional public meetings after the completion of the planned public comment period.

TECHNICAL BASIS FOR NEW REGULATORY GUIDANCE

During public meetings, the NRC staff stated that the new regulatory guide would include the following features:

1) the ASCE/SEI 43-05 performance-based approach
2) an annual mean target performance goal for seismically induced onset of significant inelastic deformation (i.e., a FOSID goal of $1x10^{-5}$)
3) optional use of CAV filtering for PSHA
4) generic soil amplification approaches as outlined in NUREG/CR-6728, "Technical Basis for Revision of Regulatory Guidance on Design Ground Motion: Hazard and Risk-Consistent Ground Motion Spectra Guidance," issued October 2001 [8], specifically procedures 2A, 2B, 2A/3, and 2A/4

Target Performance Goal

The NRC staff has examined the various facets of the intertwined issues associated with the choice of a target performance goal. The staff has concluded that the approach described in ASCE/SEI 43-05 for Seismic Design Basis 5D, which targets a mean annual FOSID value of $1x10^{-5}$, is an acceptable approach. The ASCE/SEI standard is a national consensus standard, and the NRC staff and its consultants have thoroughly reviewed and evaluated applicable portions of the standard [18]. The target performance goal is based, in part, on the reference probability of a median $1x10^{-5}$ used in Regulatory Guide 1.165 and on the typical frequencies for existing NPPs examined in the NRC Individual Plant Examination of External Events program [19]. The NRC staff also reviewed EPRI reports regarding the assessment of existing NPP design-bases ground motions for the updated seismic hazard using PSHA. Based on this review, the staff concluded that the ASCE/SEI 43-05 approach using the FOSID mean annual target performance goal of $1x10^{-5}$ is reasonable.

TECHNICAL CONTENT OF REGULATORY GUIDE 1.208

The NRC has developed Regulatory Guide 1.208 to provide general guidance on methods acceptable to the staff for the following:

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
5) determining a site-specific, performance-based GMRS[2]
6) satisfying the requirements of 10 CFR 100.23
7) leading to the establishment of an SSE to satisfy the design requirements of Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities"

Regulatory Guide 1.165 provided general guidance on procedures acceptable to the NRC staff to satisfy the requirements of 10 CFR 100.23. The new Regulatory Guide 1.208 includes alternative guidance that incorporates 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 GMRS.

The general process to determine a site-specific, performance-based GMRS includes the following elements:

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

Site- and region-specific 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 interpretations are consistent with the information used in probabilistic seismic hazard studies previously accepted by the NRC.

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 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.

Regarding the site response analysis to incorporate the effects of local geology and topography, 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 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 and the western United States has been developed to determine the dynamic site response for the soil or rock site conditions [8].

Regarding the selection of appropriate performance goals and methodology, Chapters 1 and 2 of ASCE/SEI 43-05 describe a performance-based approach, instead of the reference probability approach described in Appendix B to Regulatory Guide 1.165.[3] The performance-based approach employs target performance goal (P_F), probability ratio (R_P), and hazard exceedance probability (H_D) criteria[4] to ensure that NPPs can withstand the effects of earthquakes with a desired performance, expressed as the target value of 1×10^{-5} for the mean annual probability of exceedance (frequency) of the onset of significant inelastic deformation (FOSID[5]). This approach targets a performance criterion for SSCs that is defined relative to the onset of

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2 Site-specific GMRS are characterized by horizontal and vertical response spectra determined as free-field motions on the ground surface or as free-field outcrop motions on the uppermost in situ competent material using performance-based procedures. When the GMRS are determined as free-field outcrop motions on the uppermost in situ competent material, the site response analysis includes only the effects of the materials below this elevation.

3 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 central and eastern United States. The sites selected were intended to represent relatively recent (to the study) designs that used the Regulatory Guide 1.60 [7] design response spectrum, or a similar spectrum, as the design bases. The use of the reference probability ensures an adequate level of conservatism in determining the SSE, consistent with recent licensing decisions.

4 The P_F, R_P, and H_D criteria corresponding to Seismic Design Category 5 [10], which are equivalent to NPP requirements, are used.

5 The annual probability of the onset of significant inelastic deformation (OSID) is just beyond the occurrence of insignificant (or localized) inelastic deformation, and in this way corresponds to "essentially elastic behavior." As such, the OSID of an SSC can be expected to occur well before seismically induced core damage, resulting in much larger FOSIDs than SCDF values. In fact, OSID occurs before SSC "failure" if the term failure refers to impaired functionality.

inelastic deformation rather than relative to the occurrence of failure of the SSC. The mean annual probability of exceedance associated with this performance target was chosen based on this performance criterion.

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

The SSE is the vibratory ground motion for which certain SSCs 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 GMRS at the free ground surface. The purpose of this regulatory guide is to provide guidance on the development of the site-specific GMRS. The GMRS satisfy the requirements of 10 CFR 100.23 with respect to the development of the SSE. In the performance-based approach described in this guide, the GMRS are based on the site-specific UHRS at the free-field ground surface, 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.

The steps necessary to develop the final SSE are described in Chapter 3 of NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," issued March 2007 [20]. This process is defined by several options that involve the use of operating license applications using a preapproved site permit and a certified design of specific reactor type (or various other combinations of new sites with certified or noncertified reactor designs). When a combined operating license application uses a standard design, standard designs have broadband smooth response spectra, referred to as certified seismic design response spectra (CSDRS[6]). The CSDRS are site-independent seismic design response spectra scaled to a peak ground motion value. Under the first option or combined license procedure, the GMRS are used to determine the adequacy of the CSDRS for the site. If adequate, the CSDRS become the SSE for the site. Alternatively, under another option, an applicant would develop a site-specific NPP design based on a site SSE. For some sites, the GMRS might not contain adequate energy in the frequency range of engineering interest and, therefore, might not be appropriate as the site-specific plant SSE. For these situations, the GMRS could either be broadened or enveloped by a smoothed spectrum.

During the design phase, an additional check of the ground motion is required at the foundation level. According to Appendix S to 10 CFR Part 50, the foundation level ground motion must be represented by an appropriate response spectrum with a peak ground acceleration of at least 0.1 g. Chapter 3 of NUREG-0800 describes the steps necessary to determine the final SSE, such as the acceptability of the CSDRS for a given site and the minimum seismic design-basis requirements.

CONCLUSIONS

Regulations for seismic siting and design of NPPs have evolved over last 30 years, consistent with the development in the state-of-the art in seismic hazard analysis and understanding of the risk to NPPs. Development of these regulations is reviewed; beginning with the criteria in 10 CFR Part 100 Appendix A, used for the existing NPPs (1973-1997), to the revised regulations in 10 CFR 100.23 (1997), explicitly accepting the PSHA, as described in Regulatory Guide 1.165; and the recently issued current guidelines in Regulatory Guide 1.208, based on the risk-informed performance-based approach.

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