Probabilistic Seismic Hazard Assessment Activities, Including Continuing Research, at the U.S. Nuclear Regulatory Commission

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ABSTRACT

Probabilistic seismic hazard assessment (PSHA) is a method for estimating the annual frequency of exceeding a particular earthquake ground motion at a site and for capturing the uncertainties associated with that estimate. The U.S. Nuclear Regulatory Commission (NRC) has made a commitment to the use of PSHA and its future enhancements, which has led to an advocacy for its widespread use.

This paper examines the following three phases of the utilization of PSHA at the NRC:

(1) development and rationale/justification
(2) practical application in a regulatory environment
(3) continuing enhancement and refinement

Under the first phase, the NRC worked with the innovators of the probabilistic hazard method to develop an approach to address the fundamental issues associated with the "deterministic" approach to siting critical facilities, such as nuclear power plants, dams, and liquefied natural gas storage and handling facilities. These fundamental issues include the following:

- What are the uncertainties in the deterministic parameters used to describe the hazards of concern?

- Are there abrupt cliffs in the boundaries of the hazard estimates?

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- Can the estimates of the hazards be better described to limit contention among experts, users, and regulators?

- Is there a better seismic hazard characterization methodology?

This first phase led to the development and implementation of the Lawrence Livermore National Laboratory and Electric Power Research Institute PSHAs for the Eastern and Central United States, to the preparation of the guidance of the Senior Seismic Hazard Analysis Committee (SSHAC), and to the writing of NRC Regulatory Guide 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion," issued March 1997.

A principal activity during the second phase, which made extensive use of PSHA to address seismic vulnerabilities, was the individual plant examination of external events program (IPEEE). The staff used PSHA results to develop the scope of the search for vulnerabilities conducted by individual plants. PSHAs, following the new Regulatory Guide 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion," issued March 2007, are being submitted for a new generation of early site permit and combined operating license applications. (A complementary paper at this workshop by Li and Chokshi will cover this particular aspect of PSHA utilization.[2])

While this paper briefly describes the first two phases, the heart of the paper is the third phase, enhancement and refinement of the PSHA process. The Seismic Research Program Plan from the NRC's Office of Nuclear Regulatory Research contains the agency's goals for the third phase. The plan, in part, starts from the premise that PSHA has achieved a level of maturity and utilization and lays the foundation for the next generation of PSHA. The elements in the plan pertinent to this workshop include the following:

- seismic source characterization for the Central and Eastern United States (CEUS)

- development of a next-generation attenuation relationship for the CEUS

- lessons learned from the practical application of the SSHAC guidance

- analysis of the effects of the application of cumulative absolute value (CAV) filtering

Introduction

Probabilistic seismic hazard assessment (PSHA) is a method for estimating the annual frequency of exceeding a particular earthquake ground motion at a site and for capturing the uncertainties associated with that estimate. The U.S. Nuclear Regulatory Commission has used this method since the late 1970s and early 1980s, first as a research tool to better understand the boundaries or uncertainties associated with deterministically derived design ground motion parameters and the resultant seismic safety margins of nuclear power plants (NPPs). Then, in the 1990s, as the NRC moved toward the use of risk-informed and performance-based principles, PSHA was introduced into regulatory guidance. This paper will briefly look at two historical phases of the

[2] Y. Li and N.Chokshi, 2008, "Seismic Source Issues in Siting New Nuclear Power Plants in the Central and Eastern United States", Proceedings of the CSNI Workshop on Recent Findings and Developments in PSHA Methodologies and Applications, OECD/NEA, Paris, France

development and implementation of PSHA at the NRC and then examine the ongoing and planned research that will support or augment its future regulatory uses.

Phase I: Probabilistic seismic hazard assessment development and rationale/justification

The development of PSHA came to a critical nucleation stage in the early 1980s with the initiation of a program at Lawrence Livermore National Laboratory (LLNL).[3] The goal of the program, entitled "Seismic Hazard Characterization Project for the Eastern United States," was to develop a probabilistic methodology and software package to calculate hazard estimates and their uncertainties. Two of the stimuli for the project were (1) the need for a simplified method to characterize the seismic hazard as an input for the Seismic Safety Margins Research Programs and (2) the need for a rapid resolution to address the so-called Charleston Earthquake Issue. (The Charleston Earthquake Issue involved a technical position regarding seismic hazards in the eastern United States taken by the U.S. Geological Survey (USGS). It stated that while there was no recent or historical evidence that sites along the eastern seaboard had experienced an earthquake similar to the 1886 Charleston earthquake, the historic record was not a sufficient basis to rule out the possible occurrence of such an earthquake. The USGS noted that the probability of such an event might be very low at a given location.)

Given the novelty of PSHA in the early 1980s, the NRC urged the nuclear power industry to develop its own approach to PSHA. In response, the Electric Power Research Institute (EPRI) developed the industry approach to the challenge. The result was that two methodologies were available (one from LLNL and one from EPRI), and they provided conflicting hazard estimates for the sites evaluated. In the absence of any knowledge of the "true" hazard, the conflicting hazard estimates presented the NRC with a regulatory dilemma. While the rank orderings of the NPP sites in the central and eastern United States (CEUS) were similar (i.e., sites with high hazard estimates were high in both studies, and sites with low hazard estimates were low in both), the absolute values of the hazard estimates differed by as much as an order of magnitude.

The NRC, in cooperation with the U.S. Department of Energy (DOE) and EPRI as a DOE partner, assembled a committee of senior experts, the Senior Seismic Hazard Analysis Committee (SSHAC), to write guidance on how to conduct a PSHA.[4] The SSHAC concluded that the differences in the LLNL and EPRI PSHA results were primarily the result of procedural rather than technical differences. The SSHAC guidance focused, in part, on the use of experts from whom hazard input parameters would be elicited. The SSHAC guidance has been a standard against which complex PSHA studies, such as the Yucca Mountain repository PSHAs and the Swiss PEGASOS study, can be conducted or judged.

Phase II: Practical application in a regulatory environment

Revision of seismic siting criteria

In 1996 and 1997, the NRC completed the revision to the seismic siting and engineering criteria and the accompanying regulatory guides and sections of the Standard Review Plan (NUREG-0800). The siting criteria can found be found in Title 10, Section 100.23, "Geological and

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[3] D.L. Bernreuter, et al., 1985, "Seismic Hazard Characterization of the Eastern United States: Methodology and Interim Results for Ten Sites," NUREG/CR-3756, U.S. Nuclear Regulatory Commission, Washington, DC.
[4] R.J. Budnitz, et al., 1997, "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts," NUREG/CR-6372, Vols. 1 and 2, U.S. Nuclear Regulatory Commission, Washington, DC.

Seismic Siting Criteria," of the *Code of Federal Regulations* (10 CFR 100.23),[5] with the engineering aspects covered in Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants," to 10 CFR Part 50.[6] The requirements in 10 CFR 100.23 significantly simplified the criteria from the prescriptive, deterministic criteria of the old regulation to a process requiring uncertainty analysis and allowing the use of PSHA for the required uncertainty analysis. Regulatory Guide 1.165,[7] published in 1997, described an acceptable way to carry out a PSHA, along with a specific probability to fix the level of the PSHA and initial guidance on the updating of a PSHA from the content of the original LLNL and EPRI PSHAs.

Individual plant examination of external events program

In the late 1980s, the NRC initiated the individual plant examination of external events program to identify any potential vulnerabilities in NPPs to severe accidents initiated by external events, including internal fires, earthquakes, floods, and high winds. For seismic events, the program made use of the two available PSHAs to establish the level of ground motion to be applied in the plant examination. The NRC guidance allowed the use of either the seismic probabilistic risk assessment (PRA) or the seismic margins analysis (SMA) methodologies to detect potential vulnerabilities. About two-thirds of the respondent NPPs used the SMA method to examine their plants for potential vulnerabilities, and the remaining one-third used seismic PRAs. The NPPs that used PRAs made direct use of PSHAs as input to the PRAs, while those that used SMAs used PSHAs indirectly because the PSHAs had been incorporated in the development of the SMA method.

U.S. nuclear renaissance

Since 2002, licensees have begun to actively consider new plant construction. Four early site permit (ESP) applications and 11 combined operating license (COL) applications having been submitted to the NRC for approval *as of March 25, 2008*.

Early site permit applications

Clinton	*Issued*
Grand Gulf	*Issued*
North Anna	*Issued*
Vogtle	*Under Review*

Combined operating license applications

Bellefonte Nuclear Site Units 3 and 4
Calvert Cliffs Unit 3
Grand Gulf Unit Unit 3
North Anna Unit 3
Shearon Harris Units 2 and 3
South Texas Project Units 3 and 4
William States Lee III Units 1 and 2

All of these applications have used PSHA in determining their design-level ground motion

[5] *U.S. Code of Federal Regulations*, Title 10, Energy, Part 100, "Reactor Site Criteria."
[6] *U.S. Code of Federal Regulations*, Title 10, Energy, Part 50, "Domestic Licensing of Production and Utilization Facilities."
[7] U.S. Nuclear Regulatory Commission, 1997, Regulatory Guide 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion," Washington, DC.

parameters, with the majority following the guidance in Regulatory Guide 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion," issued in March 2007. This new guide represents growth and evolution since Regulatory Guide 1.165.

Phase III: Enhancement and refinement of probabilistic seismic hazard assessment—current seismic research activities and plans[8]

Background and scope

In the early and mid-1990s, the NRC began to move its siting and design review processes toward the use of a probabilistic, performance-based regulatory approach. Toward that end, in the late 1990s and again in 2007, the NRC published a new set of geological and seismological siting criteria and associated regulatory guidance (Refs 5 and 6). That guidance described a probabilistic approach that can explicitly quantify and address both natural aleatory variability and epistemic uncertainty. The uncertainty associated with the determination of the maximum credible earthquake for each NPP or other nuclear facility can be significant because of the wide range of scientific opinion and the range in the sources and quality of the input data.

The NRC and the nuclear industry have incorporated a risk-informed, performance-based approach for the analysis, design and regulation of NPPs. The American Society of Civil Engineers (ASCE) has provided some of the technical basis for incorporating performance-based design through its standard ASCE/SEI 43-05.[9] The goal of that standard is to provide seismic design criteria to ensure that safety-related structures, systems, and components are sufficiently robust to withstand earthquake effects. This goal is attained through regulatory guidance ensuring that nuclear facilities can be designed to achieve quantitative probabilistic target performance goals.

In developing this seismic research program, the NRC staff identified projects that address specific regulatory issues or requirements. Some of the research needs identified arose during the implementation and regulatory review of probabilistic or risk-informed performance-based approaches. In some cases, the plan identifies cutting-edge research to inform future regulation or regulatory guidance. Other research activities are intended to independently assess the adequacy of proposals or approaches forwarded by industry. In all cases, research has been focused and designed to meet the regulatory goals of the NRC, and regulatory products have been identified.

Selected research program elements

Seismic source characterization

Seismic source characterization is a key issue for the NRC because it is a major contributor to uncertainty in seismic hazard assessments. The research needs for this topic are significant, particularly in regions that tend to have rare (although often large) events and have limited seismic instrumentation (i.e., the CEUS). Current NRC research involves a study on the maximum magnitude (M_{max}) appropriate for seismic sources in the CEUS and further study/characterization of the East Tennessee Seismic Zone. An additional long-term goal is the enhanced understanding of the seismogenic processes and characteristics of the New Madrid, Charleston, and other earthquake source zones for which uncertainties are high. To address this specific goal, the NRC is working with

[8] U.S. Nuclear Regulatory Commission, 2008, "NRC Seismic Research Program Plan—FY2008–2011," NRC Online Web Site, Agencywide Documents Access and Management System (ADAMS) Accession No. ML072960789, Washington, DC.
[9] American Society of Civil Engineers/Structural Engineering Institute, 2005, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities," ASCE/SEI 43-05.

DOE and EPRI to develop a multiagency, multiyear project to recharacterize the seismic hazard sources in the CEUS.

Another key area of uncertainty that warrants research (in the long term) is the functional form and magnitude recurrence relationships for background (area source) seismicity in the CEUS. Finally, a study of the impact and technical basis of different approaches to incorporating background seismicity in the hazard calculations is needed. The following paragraphs describe each of these significant issues in greater detail.

M_{max} is a parameter with large uncertainty in the CEUS that can raise the hazard at a site, particularly if the hazard is dominated by background seismicity. This parameter does not have a significant impact on hazard results for the return periods of interest for more conventional structures or the U.S. National Seismic Hazard Maps (e.g., return periods of 474 to 2475 years).[10] However, for return periods of interest to current NRC licensing activities (e.g., return periods of 10,000 to 100,000 years), this parameter may be very important. For that reason, the NRC initiated research related to this topic at the end of fiscal year (FY) 2007 and will continue to undertake that research in cooperation with USGS through FY 2008.

The East Tennessee Seismic Zone is an area of comparatively high seismic activity, located relatively close to several operating NPPs. The underlying tectonic basis for the increased activity in this area is unclear; hence, the most appropriate estimates for zone boundaries, seismogenic depth, and maximum magnitude are also unclear. The NRC will coordinate research on this topic with USGS, with the participation of both academic researchers and USGS staff.

Analysts may characterize seismic zones through the use of a number of complementary techniques, such as fault trenching and traditional field techniques. Recently, other traditional field techniques have been coupled with new technology-based field techniques, such as light detection and ranging (LiDAR), which is essentially a powerful laser-based imaging system mounted on an aircraft. LiDAR, in particular, has proved extremely useful for areas with dense vegetation and has led to a significant revision of fault mapping in the Pacific Northwest. Another successful methodology developed through past NRC support is the use of paleoseismic and paleoliquefaction studies. These types of studies may be of particular interest in the New Madrid and Charleston regions, where liquefaction occurred regionally. Another technique that has been used extensively is the correlation of historical accounts and physical effects (such as the New Madrid earthquakes) with intensity data, which is then correlated with ground motions. Finally, new cutting-edge techniques have been developed for research related to the planned high-level waste repository at Yucca Mountain that help to constrain loading levels for extreme events.

Next-generation attenuation models for the Central and Eastern United States

The prediction of ground motions for a given magnitude and distance has always constituted a significant source of uncertainty in seismic hazard results. Uncertainty in these relationships leads to differences in the hazard levels calculated. This is at least partly a result of the ad hoc nature of the past development of these relationships. The research proposed in this area will seek to follow up on the very successful multi-institutional, multi-investigator, multisponsor, collaborative project, known as the next-generation attenuation relationship project or the NGA-West project. This project, which was coordinated by the Pacific Earthquake Engineering Research Center, produced a set of consensus relationships that are now viewed as the state of the art/practice. This paper describes a program for

[10] A. Frankel, et al., 2002, "Documentation for the 2002 Update of the National Seismic Hazard Maps," Open-File Report 02-420, U.S. Geological Survey, Reston, Virginia, United States.

conducting NGA-East.

Because the NGA-East program represents a significant financial investment, and because the results will be of interest to many stakeholders, an NGA-East development project will be undertaken to obtain funding and support from these stakeholders. This project will develop the broader NGA-East program plan, deliverable details, timeline, and cost estimates and will explore partnering options.

If a very large data set of ground motion recordings were available, it would be possible to develop robust empirical relationships for ground motion prediction in the CEUS. However, that is clearly not the case. Empirical data in the magnitude, distance, and amplitude ranges of engineering interest are very sparse. As a result, all predictive equations developed thus far have relied heavily on ground motion simulations to augment the very limited empirical data set, and the proposed NGA-East program will need to follow the same path. Evaluation of the past work has revealed several important assumptions and parameters that have a significant influence on the resulting predictive equations. The planned or ongoing elements of the NGA-East project are development of a time-history database, stress drop/parameter, spectral shape, strong ground motion simulation for finite sources, and NGA-East model development program. It is anticipated that the complete NGA-East program will take several years to complete.

Updating the Senior Seismic Hazard Analysis Committee guidelines

In an effort to standardize approaches to PSHA, the NRC sponsored the development of NUREG/CR-6372. That document (referred to as the "SSHAC guidelines") offers guidance for conducting a PSHA at four different levels of complexity depending on project needs. Level 4 PSHAs represent the most complex, controversial, and challenging undertakings, while Level 1 describes more routine analyses. While the SSHAC guidelines provide a framework for the various levels of PSHA, feedback from the initial workshop of this project indicates that the document does not provide sufficient detail on how to implement PSHAs readily at the various levels.

Subsequent to the publication of NUREG/CR-6372, practical experience in conducting Level 3 and 4 PSHAs in accordance with the SSHAC guidelines has been gained through Yucca Mountain, the Swiss PEGASOS Project, and the EPRI CEUS Ground Motion Project Final Report. However, this experience has not been captured in a form that could benefit an organization that was anticipating conducting or reviewing a major PSHA effort. In addition to the need to provide practical information on the implementation of PSHAs at the various levels, guidance is needed on how PSHAs are updated. Currently, NRC Regulatory Guide 1.208 requires PSHAs to be updated as new information regarding seismic sources or new tools (such as new attenuation relationships) become available.

The objective of this task is to develop a NUREG-series report that will complement the existing PSHA-related regulatory guidance by achieving the following goals:

- Provide practical guidelines for implementing the NRC's SSHAC framework when undertaking PSHAs.
- Capture lessons learned during SSHAC Level 3 and 4 projects nearing completion, such that future high-level PSHAs require less effort.
- Provide practical guidelines for updating SSHAC-based PSHAs when new information, such

as seismic sources or models, becomes available.

As a result of this work, future PSHA programs will be more uniform and complete and, therefore, more easily and efficiently reviewed by the NRC staff. USGS will manage this task, with the participation of industry and academic researchers. The NRC initiated this work in FY 2007 and held the first of three planned workshops in January 2008. It collected information and experience on the use of the SSHAC guidance for SSHAC Level 3 and 4 PSHAs. The second workshop, planned for May 2008, will address the issue of updating a Level 3 or 4 PSHA for both timing and content. (Additional comments on the SSHAC update project are provided in a complementary paper at this workshop by Ake.[11])

Enhanced monitoring of seismic activity in the central and eastern United States

Currently, there are portions of the central and eastern United States in which seismic instrumentation is limited. Additional seismic monitoring equipment to provide enhanced coverage near NPPs would be benefical in assessing plant safety following a seismic event. The installation and operation of seismic monitoring stations by the NRC as an in-house activity is problematic. NRC staff is currently pursuing opportunities to support expansion of the Advanced National Seismic System (ANSS) to areas that are of interest to the agency (i.e., near nuclear facilities or regions of enhanced seismic activity) that are not well-covered by the existing system. This partnership would provide substantial leverage to the NRC investment.

Multi-dimensional loading in site response analyses

Traditionally, site response analyses have been performed using the assumption of one-dimensional (1D) loading, both at the element level and a site-scale level. Recent research has led to the recognition that this assumption may not be appropriate for some sites. Observations of strong basin effects, the potential impact of dipping and faulted impedence boundaries, and research on two-dimensional (2D) liquefaction testing at the element level have all served to highlight the potential importance of multi-dimensional loading in site response analyses. This is a developing research area that the NRC is monitoring and will be undertaking research activities in the future.

Analyses of extreme ground motion

Studies performed in the past decade for the Swiss nuclear program (the PEGASOS Project) and Yucca Mountain have highlighted the difficulties in predicting ground motions for very low annual probabilities of exceedance. Recently, significant research has focused on understanding "extreme" ground motions (i.e., very rare, but very large motions) and the implications for hazard estimates for critical facilities. Even more recently, the implementation of a risk-based approach to ground motion hazard evaluation for nuclear facilities has led the NRC staff to recognize that issues associated with extreme ground motions may be important for facilities other than Yucca Mountain.

A number of questions and issues emerge from consideration of extreme ground motions in hazard analyses. These include the following:

- The use of equivalent linear versus nonlinear site response. When are nonlinear studies

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[11] J. Ake, 2008, "Uncertainties in PSHA for Regions of Low-to-Moderate Seismic Potential: The Need for a Structured Approach, ", Proceedings of the CSNI Workshop on Recent Findings and Developments in PSHA Methodologies and Applications, OECD/NEA, Paris, France

required (or when are equivalent linear studies inappropriate)? When is it appropriate to use site response techniques based on random vibration theory?

- The development of modulus degradation and damping curves for rock materials. Issues include the availability and characteristics of capable laboratory testing equipment, the possible use of other less-traditional methods (e.g., shake table testing), the systematic bias in samples (e.g., generally the best material is tested because of minimal sample recovery in the weaker materials), the potential for systematic bias if samples are not large enough to allow accurate assessment of the effects of inclusions or fractures, and the correlation between static and dynamic properties.

- The development and use of the "points in hazard space" concept and method. This is a new conceptual approach that relies on augmenting sparse conventional data at high-amplitude, low-probability regions of hazard space with constraints based on physical limits and/or nonexceedance observations. These constraints may then be used in a mathematical framework to update or inform existing hazard estimates. This approach may be of great interest for very long return periods. Although the NRC is not currently funding efforts in this area, DOE has funded initial work in this area.

- The NRC research effort is focused on the continued improvement and development of correlations between intensity and empirical evidence, instrumental observations, and geotechnical observations. The results of this work will be used to better quantify the seismic history for locations where the largest earthquakes have occurred in the preinstrumental period.

Development of shape of minimum response at foundation level

Past regulatory guidance provided acceptable response spectra to be used in analyzing and designing NPPs and other nuclear facilities. The earliest versions of these spectra were detailed in Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants," Revision 1, issued December 1973, and later updated slightly in Regulatory Guide 1.165. The spectrum provided in Regulatory Guide 1.60, in particular, has a long history in NPP design and has also been used as the basis for the standard facility design in the past.

While the spectrum detailed in Regulatory Guide 1.60 was state of the art when it was developed in the 1970s, it was based on only a handful of records that constituted the database of recordings available at the time. New data and attenuation relationships predict differences between uniform hazard response spectra and the standard design spectral values at high frequencies for many sites. Consequently, new standard design spectra more in line with current knowledge and the state of practice are needed. Currently, thousands of earthquake records are available, and new attenuation relationships based on this expanded database are now available for the western United States (WUS). In addition, the NGA-East program (discussed above) will provide an updated tool for use in developing generic response spectra for the CEUS.

Although the determination of the seismic hazard has moved to a site-specific probabilistic framework, the use of some alternative minimum spectrum is needed as a result of regulatory requirements and the significant epistemic uncertainties in the source models and attenuation relationships that exist for the CEUS. There is also a need to define a standard structural response spectrum to be used in the standard design of new plants and evaluation of existing NPPs and other nuclear facilities.

Analyses of the effects of cumulative absolute velocity filtering on probabilistic seismic hazard assessment

Standard design methods use a structural response spectrum as the means to describe the seismic hazard used in design. The response spectrum, which is defined in terms of accelerations versus natural frequency, provides the single highest value of motion in single-degree-of-freedom structures resulting from an imposed ground motion. This is a good indicator of damage potential for many cases (e.g., in the WUS) but can overstate damage potential when small, close earthquakes are a significant contributor to the overall hazard. This is because the response spectrum shows only the maximum motions, but small, nearby earthquakes have, at most, a few cycles of significant motion and the total energy is too low to cause damage.

The new technique of cumulative absolute value (CAV) filtering has the effect of removing from the sources included in the PSHA low-magnitude earthquakes that have insufficient energy to cause damage to facilities. The purpose of removing these events is to produce a spectral shape that correlates more directly with the risk of damage to a facility. Thus, removing these events from the PSHA effectively changes the shape of the resulting site response spectra in the high-frequency range, with the biggest change typically occurring over higher annual exceedance frequencies in which these small events are the biggest statistical contributor to the overall hazard as it is defined by the response spectra.

However, the performance-based procedures detailed in ASCE/SEI 43-05, which were developed to ensure a specific target performance goal for the frequency of seismically induced onset of significant inelastic deformation (FOSID), have assumed that the hazard curves are approximated by a power law equation (i.e., linear on a log-log plot) in the annual probability of exceedance range of $1x10^{-4}$ to $1x10^{-5}$. The application of CAV filtering in regions of low seismic activity may render this assumption inappropriate, and, in fact, the value of the hazard curve at some return periods may become zero for one or both of these values. This has a significant impact in terms of ensuring that the FOSID target performance goal is met. Consequently, it has been proposed that, in these cases, the hazard value for the annual frequency of $1x10^{-4}$/year should be approximated as 45 percent of the value for the annual frequency of $1x10^{-5}$/year. This assumption is thought to be conservative, but the degree of conservatism has not yet been quantified.

This new project will involve analyzing the actual likely impact of CAV filtering on the shape of the hazard curves to determine whether the power law assumption is inaccurate in some cases. For such cases, the researchers will review the validity of the proposed solution in cases where the hazard defined at the annual frequency of $1x10^{-4}$/year level goes to zero.

Tsunami hazard evaluation

The Sumatran earthquake in December 2004 (magnitude of about 9) and the associated devastating Indian Ocean tsunami focused considerable attention on structures and facilities that are sited on or close to the coastline. The intensity of an extreme tsunami event could potentially exceed known historical events considered in the design bases of NPP structures or other nuclear facilities located near the coastline. In addition, although past tsunami design of coastal facilities considered historical tsunami records, it did not explicitly address a tsunamigenic source known as "submarine landslides," which can trigger significant tsunami waves.

Given these concerns, the NRC is currently working with the National Oceanic and

Atmospheric Administration (NOAA) and USGS to review the existing state of knowledge for the tsunami hazard assessment, mitigation, and landslide mechanics. In May 2006, NOAA and USGS scientists briefed the NRC staff on the research and state of knowledge for both earthquake- and landslide-induced tsunamis. This meeting initiated research efforts in the area of tsunami hazard assessment. In October 2006, an advisory panel of tsunami experts from USGS and NOAA provided a draft document summarizing the state of knowledge on tsunami hazard assessment for use in updating the Standard Review Plan (NUREG-0800).[12]

In addition, in 2006, the NRC initiated a long-term, multiphase plan to undertake a deterministic or, if possible, probabilistic tsunami hazard assessment (DTHA or PTHA) for the east and gulf coasts of the United States. This additional research will significantly improve the technical basis of the agency's existing knowledge by providing a state-of-the-art assessment of tsunami hazard in the time periods of interest to the NRC. This type of knowledge for the east and gulf coasts of the United States is currently very limited.

The first step in conducting either a DTHA or PTHA is to identify and characterize tsunamigenic sources that may impact the east and gulf coasts of the United States. USGS is undertaking this work, and the sources identified include both seismic sources and submarine landslides. The draft database of tsunamigenic sources was finalized in September 2007. This database will be used in reviewing new applications on the east and gulf coasts

The next steps in the long-term plan include using field techniques to obtain data for areas where no data previously existed, and modeling the impact of the tsunami sources identified and detailed in the database. This Phase 2 research was initiated in late 2007. USGS will continue with source investigation and analysis. NOAA will undertake the modeling work by using its in-house, state-of-the-art tsunami propagation model, MOST. NOAA will also use the source database developed by USGS to model the impact of the sources on the east and gulf coasts in terms of wave heights and maximum ocean surface fluctuations over time periods of interest. This work will provide hazard mapping for the east and gulf coasts.

A key element of both the source database development and the MOST modeling is the inclusion of landslide sources. While it is understood and documented that landslides cause localized tsunamis, this triggering mechanism is of interest only when considering rare events (such as those considered for nuclear facilities). For this reason, very little research has been done in this area, and a high degree of uncertainty currently exists. This program will be a significant step forward in bounding the uncertainties associated with tsunami hazard on the east and gulf coasts. The final stage of the hazard assessment will be basic site-specific inundation modeling for the coastline, and a long-term goal of the project is to develop maps for the east and gulf coasts.

Conclusions

The NRC has adopted the use of PSHA as a tool in the siting of critical facilities, such as NPPs and the Yucca Mountain high-level waste repository. PSHA provides a method for estimating design ground motion parameters and their uncertainties. Other U.S. scientific and regulatory agencies, such as USGS[13] and the Bureau of Reclamation,[14] have adopted this method, which has been

[12] U.S. Nuclear Regulatory Commission, 2007, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," NUREG-0800, Washington, DC.

[13] A. Frankel, et al., 2002, "Documentation for the 2002 Update of the National Seismic Hazard Maps," Open-File Report 02-420, U.S. Geological Survey, Reston, Virginia, United States.

[14] U.S. Department of the Interior, Bureau of Reclamation, 2003, "Guidelines for Achieving Public Protection in Dam Safety

approved by the U.S. Academy of Sciences.[15] The NRC is undertaking a research program to enhance the utility and accuracy of PSHA. The NRC is also conducting research in tsunami hazard assesssment with the prospect of developing a probabilistic, performance-based approach for tsunami, as well as other natural hazards such as flooding.

Decision-making," Denver, Colorado, United States.

[15] Committee on Seismology, 1988, "Probabilistic Seismic Hazard Analysis," National Academy Press, Washington, DC.