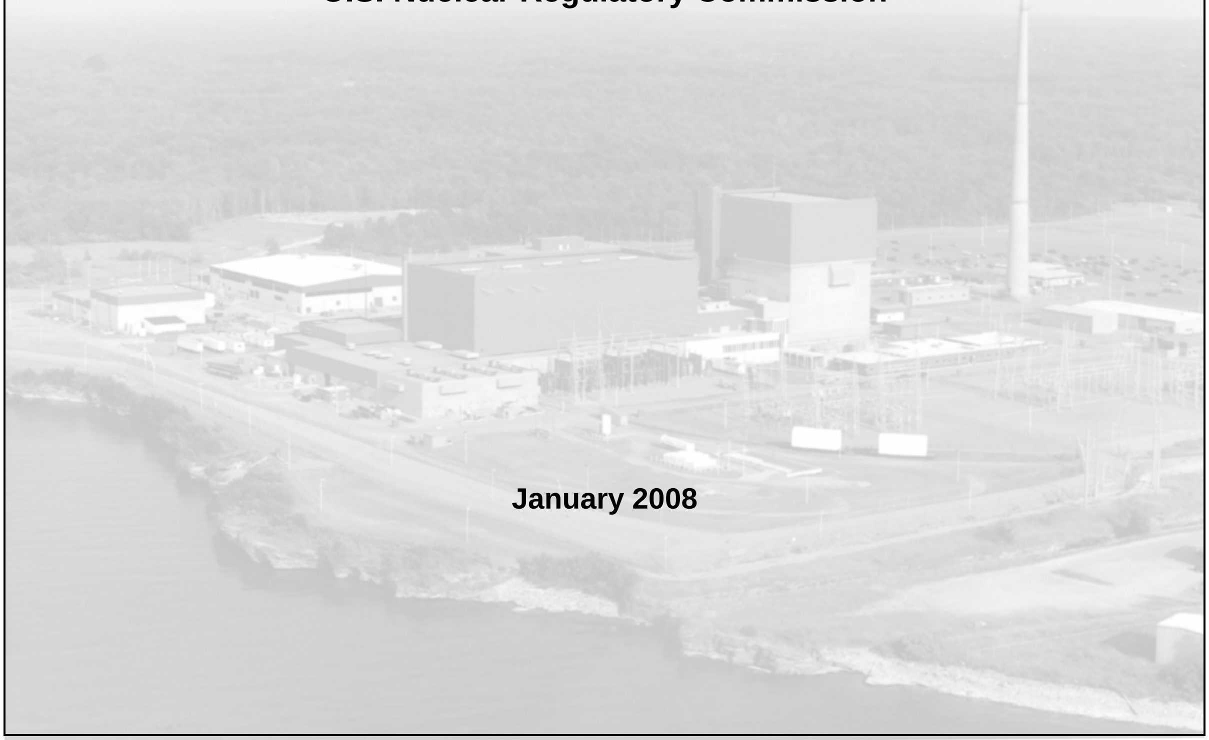
NRC Seismic Research Program Plan
FY 2008–2011

Structural, Geotechnical & Seismic Engineering Branch
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission



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1 INTRODUCTION

This Seismic Research Program Plan describes a subset of the research programs, projects, and tasks that the Office of Nuclear Regulatory Research (RES) is currently conducting or planning to support the mission of the U.S. Nuclear Regulatory Commission (NRC). Specifically, this subset encompasses research endeavors in the areas of seismic design of structures, systems, and components (SSCs), as well as in the areas of seismic and tsunami-related hazard evaluations for nuclear facilities. This plan covers research to be undertaken during Fiscal Years (FY) 2008–2011. The previous version of the research plan covered FY 2006–2009.

In describing the various research programs, projects, and tasks, this program plan discusses the specific technical areas to be addressed, as well as the underlying rationales, expected products, projected schedules, and estimated resource requirements. In so doing, this plan divides the project descriptions into the four areas of (1) Natural Hazard Research, (2) Earthquake Engineering Analysis and Design, (3) Cooperative International Research Activities, and (4) Regulatory Guide Updates.

1.1 Background

Seismic safety in the design and operation of nuclear facilities has been a ongoing and evolving issue since the inception of civilian nuclear facilities. The early rules and guidance for seismic design predate the NRC, having originated in the earliest days of the Atomic Energy Commission (AEC). Initially, the treatment of seismic hazards took the form of "deterministic" regulation and guidance, under which the current fleet of nuclear reactors and facilities was designed, constructed, and licensed, and are now operated. The design of nuclear power plants (NPPs) that were licensed in this environment have undergone several review cycles, including the individual plant examinations (IPEs) and the individual plant examinations of external events (IPEEEs). These and other reviews provide the basis for confirmation that the Nation's existing NPPs are acceptably safe with respect to seismic events.

In the early- and mid-1990s, however, the NRC began to move its siting and design processes toward the use of a "probabilistic" regulatory approach. Toward that end, in the late 1990s and again in 2003, the NRC published a new set of geological and seismological siting criteria and associated regulatory guidance. That guidance described a probabilistic approach that can explicitly quantify and address both natural aleatory variability and epistemic uncertainty. This uncertainty greatly complicates the deterministic approach. 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. In addition, the ongoing improvement of seismological source models, tools, and techniques is of great use to NRC staff.

Recently, the NRC and the nuclear industry have incorporated a risk-informed, performance-based approach into the analysis and design of NPPs. The American Society of Civil Engineers (ASCE) has provided some of the technical basis for incorporation of performance-based design through its Standard ASCE 43-05, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities." As its title implies, the goal of that standard is to provide seismic design criteria to ensure that safety-related SSCs are sufficiently robust to withstand earthquake effects such that the chances of an accidental release of radioactive materials is sufficiently low. This goal is attained by providing regulatory guidance to ensure that nuclear facilities can be designed to achieve quantitative probabilistic "target performance goals."

1.2 Objective and Scope

The objective of this Seismic Research Program Plan is to detail both short- and long-term programs to meet the strategic goals of the NRC to protect public health and the environment. For that reason, elements of the research plan are intended to complete the development of the technical bases for reviewing a performance-based approach to determine a site's safe-shutdown earthquake (SSE) and design response spectra, to finalize the development of new and updated regulatory guides, to address seismic issues arising from the review of early site permit (ESP) and combined license (COL) applications, and examine knowledge that can be gained from new areas of research. Toward that end, this document describes the research projects that the NRC is currently conducting or planning to conduct in order to address the NRC's mission. In so doing, this plan identifies the specific tasks associated with each research project; discusses the specific technical areas to be addressed; and presents the underlying rationales, expected products, projected schedules, and estimated resource requirements.

In developing this research program, NRC staff identified projects that address specific regulatory issues or requirements. Some of the research needs identified arose during the implementation 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. Issues related to individual plants or that are best investigated by industry are not included in this research plan.

The NRC staff intends to update this research plan periodically to include any adjustments in seismic research activities that may be necessary to support the agency's regulatory needs. In addition, the staff will revise this plan to include additional research that may be appropriate to support the review and licensing of evolutionary nuclear reactor designs.

2 EARTH SCIENCE AND NATURAL HAZARDS RESEARCH

2.1 Background

This section presents the details regarding the earth sciences portion of the NRC's seismic research activities, focusing on topics that relate to seismic- and tsunami-related hazards (Sections 2.2–2.7 and Section 2.8, respectively).

Over the past several years, the NRC and its consultants have been performing probabilistic seismic hazard assessments (PSHAs) in order to independently validate seismic hazard levels provided in NPP applications. However, this work has revealed discrepancies between the results of NRC analyses and those performed by industry. These discrepancies are attributable, in part, to the limited seismic hazard research undertaken for the Central and Eastern United States (CEUS) over the past few decades. Consequently, the tasks proposed below focus on addressing significant areas of uncertainty that may be causing or contributing to the observed discrepancies between NRC/USGS and industry hazard values. Specifically, these areas of uncertainty are divided into the seven topics of seismic source characterization (2.2), ground motion prediction (2.3), evaluation of previous regulatory positions (2.4, 2.5, and 2.6), and process (2.7).

The NRC initiated its tsunami hazard research program following the 2004 Indian Ocean tsunami, with the objective of developing an increased understanding of tsunami hazard along the Atlantic and Gulf Coasts of the United States. This work is being undertaken in several stages, which include determining and characterizing all potential tsunamigenic sources and modeling those sources to assess their impacts along the coasts.

2.2 Seismic Source Characterization

Seismic source characterization is a key issue for the NRC because it is a major contributor to uncertainty in seismic hazard calculations. There are significant research needs in this area, particularly in areas that tend to have rare (although often large) events and have limited seismic instrumentation (i.e. the CEUS).

The issues for which the NRC has currently funded research related to seismic source characterization involve 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 (ETSZ). 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 problematic to the NRC. Another key area of uncertainty that warrants research (in the long-term) regards the functional form and magnitude recurrence relationships for background (area source) seismicity in the CEUS. Lastly, a study of the impact and technical basis of different approaches of background seismicity 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 National Seismic Hazard Maps (e.g., return periods of 474 to 2475 years). 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 FY 2007 and will continue to undertake that research in cooperation with the USGS through FY 2008.

The ETSZ is an area of relatively high seismic activity, located relatively close to a number of operating NPPs. It is unclear what the underlying tectonic basis is for the increased activity in this area (and, hence, what the most appropriate estimates are for zone boundaries, depth, and maximum magnitude). The NRC will coordinate research on this topic with the USGS, with the participation of both academic researchers and USGS staff. This work will be initiated in FY 2008 and is expected to last on the order of 2 years.

The characterization of seismic zones may be addressed using a number of complementary techniques. Fault trenching and other similar field studies have traditionally been used. However, more recently, 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 that was 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. Lastly, there are new cutting-edge techniques that 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. A targeted mix of these types of techniques may be appropriate.

Currently Contracted Tasks (FY 2007–2009)

- Conduct an analysis of the impact of M_{max} on hazard at representative sites.
- Develop a conjugate expert opinion on the most appropriate value for M_{max} within background seismic zones through an NRC/USGS workshop. This workshop will be supported by the development of a foundation document that summarizes the complete history of M_{max}-related research, which will be provided to workshop participants for review and comment prior to the workshop.
- Summarize the results of the workshop in a report. These results would be used in updating the U.S. National Hazard Maps and USGS models, which are used as the basis for performing PSHA analyses provided to the NRC staff.

Current Contract Deliverables

- Letter report on the analysis of the impact of M_{max} on hazard at representative sites.
- M_{max} workshop, including development of a foundation document detailing the complete history of M_{max} values and research.
- Report on the results of the M_{max} workshop.
- Implementation of recommendations of the M_{max} workshop in PSHAs performed for the NRC.

Upcoming Tasks (FY 2008–2010)

- Develop a white paper that summarizes the current state-of-knowledge with respect to tectonic model(s), M_{max}, zone boundaries, and potential hazard implications for the ETSZ.
- Based on the above white paper, define and initiate research to reduce uncertainty in the important properties of the ETSZ.

Upcoming Contract Deliverables (FY 2008-2010)

- White paper that summarizes the current state-of-knowledge with respect to tectonic model(s), Mmax, zone boundaries, and potential hazard implications for the ETSZ.
- USGS research reports providing data and analysis for seismic source parameters used for performing PSHAs that incorporate the ETSZ.
- Implementation of into new seismic source parameters into USGS database and in PSHAs performed for the NRC.
- Final USGS Open file report that can be used by NRC staff to independently review the seismic source parameters used by applicants for determining seismic hazard for sites that may be impacted by the ETSZ.

2.3 Next Generation Attenuation Relationship Development for the CEUS

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 discrepancies in the hazard levels calculated by the NRC staff and industry. This is a result of the ad hoc nature of the development of these relationships in the past. The research proposed in this area will seek to follow-up on the very successful multi-institutional, multi-investigator, multi-sponsor, 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 (PEER), produced a set of consensus relationships that are now viewed as the state-of-the-art/practice. The project described herein will develop a program for conducting an “NGA-East” Program.

Because the NGA-East project represents a significant financial investment, and because the results will be of interest to a large number of different agencies, an NGA-East Development Project will be undertaken to obtain funding and support from several organizations. This project will develop the broader NGA-East project plan, deliverable details, timeline, and cost estimates, and will explore partnering options with other governmental agencies. NRC, USGS, and University of California (UC Berkeley) staff will engage possible cosponsors to support the project. Other agencies that could realize significant benefit from the project include the USGS, as well as the U.S. Department of Energy (DOE), Federal Energy Regulatory Commission (FERC), Federal Emergency Management Agency (FEMA), U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and others.

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 Project 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 result of the NGA-East program is a critical-path input for research described in Sections 2.8 and 2.9, below. As such, this work was initiated in FY 2007 and has been assigned a high priority. It is anticipated that the complete NGA-East program will take several years to complete.

2.3.1 Development of a Time-History Database

Any research into ground motion prediction in the CEUS will rely on analysis of the existing database of recordings acquired in areas with similar tectonic and site conditions. This task will acquire, evaluate, and process all available, appropriate data that may be of use to the NGA-East program. This task will be directed by the USGS, in cooperation with academic researchers.

Tasks

- Identify and collect earthquake records from intra-plate and inter-mountain regions of the United States, Canada, and other similar tectonic regions.

Deliverables

- A database of earthquake records that are uniformly corrected using best practice (as described in PEER documentation) and using a standard (e.g., *.at2) format. Particular attention should be paid to identifying site conditions.

2.3.2 Stress Drop/Parameter

Most of the previous simulation work has relied on various simulation methodologies that incorporate a Brune source spectrum. This approach is widely used because it has a simple relationship to seismic source theory and only involves two parameters, seismic moment and the high-frequency stress parameter (or stress “drop”). Ignoring the seismic moment or magnitude (the simulations will be exercised over a range of magnitudes), the stress parameter is of first-order importance. This parameter directly scales the high-frequency portion of the source spectrum. Consequently, any realistic simulation scheme will need to define a median stress parameter, as well as the form of the uncertainty distribution about that median (including standard deviation), and then sample from that distribution. Historically, the assumption has been put forth that stress drops for CEUS earthquakes are greater than those observed in the western United States (WUS). However, this assumption is based on a fairly small number of observations and possibly suspect underlying assumptions. Moreover, many of the observations have not been corrected for site amplification, which will result in a positive (high) bias to any stress drop estimate. An important data set will likely be the broadband recordings from the Canadian National Seismic Network in eastern Canada. This work is likely to be conducted by the USGS, with input from other researchers.

A potentially useful corollary activity would involve evaluating the ratio between the magnitude estimates m_b and Ms (i.e., m_b/M_s). High values of m_b/M_s have been interpreted to be indicative of high values of stress drop. The importance of considering this parameter is that, in contrast to the direct stress drop data referred to above (where the entire data set is measured in the hundreds), the m_b/M_s dataset is measured in the many thousands. While it may not be easy to directly compute the median stress drop/parameter from this data set, it may prove to be very valuable for developing the form of the uncertainty distribution (i.e., log-normal or not and sigma). Some work in this area has already been funded at the USGS by DOE, and NRC participation could leverage this existing work.

Tasks

- Analyze earthquake database recordings for stress drop/parameters to inform attenuation relationship review and development.
- Compile m_b/M_s data for intra-plate and cratonic settings, and use the data to evaluate the form of the potential uncertainty in stress drop estimates.
- Compile a database of extreme m_b/M_s observations for use in evaluating the limits on stress drop.

Deliverables

- Letter report and database of extreme m_b/M_s observations for use in evaluating the limits on stress drop. This database will be used by attenuation relationship model developers as part of the NGA-East Project. The attenuation relationships developed by the NGA-East Project will be used by NRC staff in conducting independent PSHA analyses.

2.3.3 Spectral Shape

Use of recent ground motion predictive equations (i.e., attenuation functions) in the USGS hazard estimates and ESP documents suggest there is some exceedence of the SSE spectra at “high frequencies” In some locations. An important assumption that determines where the revised hazard spectra may exceed the SSE is the spectral shape. Some of the existing relationships are based on a “classic Brune” single-corner frequency model, while other relationships use a two-corner model. The two models differ significantly at the frequencies of interest for structural evaluation (i.e., 1–5 Hz). One major difference between the current USGS results and those derived by industry relates to the subjective weights assigned to the two different models. This task will be important for both the development of CEUS attenuation functions and any new, generic guidance on design spectral shape (i.e., a replacement for Regulatory Guide 1.60, “Design Response Spectra for Seismic Design of Nuclear Power Plants”).

Tasks

- Compile spectral data for earthquakes in the CEUS and Eastern Canada to evaluate the appropriateness of the two-corner model.
- Compile a similar data set for WUS earthquakes (in particular thrust mechanisms) and evaluate the similarity (or lack thereof) to CEUS data.

Deliverables

- Letter report and database of spectral data for earthquakes in the CEUS and Eastern Canada, with specific emphasis on data that address the appropriateness of the two-corner model.
- Similar data set for WUS earthquakes (in particular thrust mechanisms) for use in evaluating the similarity (or lack thereof) to CEUS data.

2.3.4 Strong Motion Simulation for Finite Sources

This research will include developing and/or refining physics-based simulation methodologies for large, nearby earthquakes, where finite-source size effects are important. The project will emphasize both deterministic low-frequency components and stochastic high-frequency (1–10 Hz) approaches. Verification (by comparison against theoretical predictions) and validation (by comparison against observations) of the simulation methodologies will continue to be an important element of this task. The results of this project will be validated against existing observations.

A current research project underway at the USGS is to develop a community-wide verification process for finite-source ground motion simulation codes. The project is a cooperative research project between the USGS and the Southern California Earthquake Center (SCEC). It may be appropriate to include the CEUS finite-source model in the USGS-SCEC verification project. This would provide significant leverage of any NRC research funds.

Tasks

- Develop and implement the new method of calculating synthetic seismograms by revising the Frankel method (1995) to include deterministic low-frequency components and high-frequency stochastic Green's functions.
- Evaluate the progress that the SCEC community project has made in using physics-based dynamic source models to develop calibrated kinematic source models.
- Validate the new method by comparing to observed seismograms and spectral acceleration values in the WUS and CEUS.

Deliverables

- Report on development and validation of the new method by comparing results to observed seismograms and spectral acceleration values in the WUS and CEUS.

2.3.5 NGA-East Development Program

As previously noted, the full NGA-East Project represents a significant financial investment, and its results will be of interest to a large number of different agencies. Thus, in FY 2007, the NRC initiated an NGA-East Development Project with the PEER Center at UC Berkeley, which will run through FY 2008. This project will develop the broader NGA-East project plan, deliverable details, timeline, and cost estimates, and will explore partnering options with other governmental agencies. The development program consists of a series of three meetings to organize the larger program and develop coordination of participation and funding among interested agencies.

Tasks

- Organize three workshops to define the deliverable details, timeline, and cost estimates, and will explore partnering options with other governmental agencies

Deliverables

- Series of three reports detailing results and key outcomes of the series of three meetings. These reports will form the basis for a broader collaborative NGA-East program.

2.4 Practical Procedures for Implementing the Guidelines of the Senior Seismic Hazard Analysis Committee and Updating Existing PSHAs

In an effort to standardize approaches to probabilistic seismic hazard analyses (PSHA), the NRC sponsored the development of NUREG/CR-6372, "Senior Seismic Hazard Analysis Committee (SSHAC) Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts." That document (referred to as the "SSHAC guidelines") provides for PSHA to be undertaken using four different levels of complexity depending on project needs. Level 4 PSHAs represent the most challenging undertakings, while Level 1 describes more routine analyses. While the SSHAC guidelines provide a framework for the various levels of PSHA, the document does not detail how to implement PSHAs at the various levels.

Subsequent to the publication of NUREG/CR-6372, practical experience in conducting PSHAs in accordance with the SSHAC guidelines has been gained at Yucca Mountain, the Swiss PEGASOS Project, and by the Electric Power Research Institute (EPRI, through its 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, there is also a need to provide guidance on how PSHAs are updated. Currently, NRC Regulatory Guide 1.208, "A Performance-Based Approach To Define the Site-Specific Earthquake Ground Motion," 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:

(1) Provide practical guidelines for implementing the NRC's SSHAC framework when undertaking PSHAs.

(2) Capture lessons learned during SSHAC Level 4 projects nearing completion, such that future high-level PSHA require less effort.

(3) 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. This task will be managed by the USGS, with participation from a number of industry and academic researchers. The NRC initiated this work in FY 2007.

Tasks

- Conduct a series of workshop-style meetings to discuss the following three topics:
  (1) lessons learned (what went right and what went wrong)
  (2) improving the SSHAC implementation guidelines
  (3) updating a PSHA (balancing practicality and the spirit of SSHAC)
- Prepare a meeting report detailing the outcome of each of the above workshops.
- Prepare a final report detailing recommendations and summarizing the outcome of the entire project (to be provided in a format appropriate for publication as part of a contractor-prepared NUREG-series report by September 2008).

Deliverables

- Three meeting reports detailing the outcome of each of the above workshops.
- Final report detailing recommendations and summarizing the outcome of the entire project.
- NRC staff will develop a NUREG based on the results and recommendations of the workshop.

2.5 Instrumentation for Independent Monitoring of Seismic Activity in the CEUS through Expansion of the Advanced National Seismic System

Currently, the seismic instrumentation in existing plants is of varying ages and accuracies. Under existing backfitting rules there is insufficient justification for the NRC staff to require update of plants to include modern seismic monitoring equipment. Coupled with this plant-specific lack of modern instrumentation, there are regions of the United States in which seismic instrumentation is limited. Additional seismic monitoring equipment to provide enhanced coverage near NPPs would be beneficial to NRC staff in assessing plant safety following a seismic event. Issues resulting from malfunctioning seismic instrumentation in NPPs were a key "lesson learned" at the Kashiwazaki-Kariwa Nuclear Power Plant. This was a problem even though the plant's instrumentation is more modern than that in many existing U.S. NPPs.

Although the installation and monitoring of seismic monitoring stations in the CEUS may be problematic for the NRC as an in-house activity, the staff would pursue opportunities to support the expansion of the Advanced National Seismic System (ANSS) to areas that are of interest to the agency (i.e., near existing NPPs and other nuclear facilities of interest) and are not currently well-covered by the existing system. Cooperative support of the ANSS or USGS (in which the NRC supports specific capital costs at locations of interest to the agency) would greatly benefit the NRC in return for a limited investment.

2.6 Multi-Dimensional Loading in Site Response Analyses

Traditionally, site response analyses have been performed using the assumption of one-dimensional (1D) loading, at both an element level and a site-scale level. However, over the past decade or more, there has been a significant increase in the awareness that this may not be appropriate (and indeed unconservative) for some sites. Observations of strong basin effects in the Northridge earthquake, the potential impact of dipping and faulted impendence 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.

On an element level, there is a fundamental understanding that soils are sheared in three dimensions during earthquakes, although very little research has been performed to assess this effect. In addition, there is now an understanding that the element-level behavior of soils under multi-directional loading (in terms of modulus degradation and damping curves) is sometimes very different than under 1D loading and is a function of ground motion rotation in addition to loading. Currently, there are only very limited datasets (for dense sands from UC Berkeley, soft clays from Texas A&M, and compacted fills from UCLA) to elucidate this effect.

In addition, 2D and 3-dimensional (3D) loading under extreme conditions may be very different. For example, “typical” partitioning of strain between components may have significant effect compared to the strong unidirectional partitioning associated with seismic source directivity.

Using tools, such as high-end finite-element (FE) methods, 2D and 3D effects can be analyzed. This is an area of cutting-edge research that the RES staff should continue to monitor to evaluate the potential impact on site response.

<u>Tasks</u>

- Perform additional laboratory testing on materials of interest to nuclear facilities to determine the impact of 2D loading of element-level soil samples.
- Using the results of the above testing, assess the accuracy of newly developed 2D soil constitutive models, and work with the developers to improve the predictive capabilities of the models.
- Identify and analyze potential case histories for sites with similar soil types. These may be sites with vertical arrays, free-field/structural instrumentation pairing, or other locations with useful seismic data collection systems.
- Using the updated soil models, perform time-domain sensitivity and analytical studies on soil-structure systems similar to those of typical nuclear facilities.
- Using simple dipping and/or faulted impedance boundaries, perform analytical studies to assess the impact on site response for typical nuclear facilities.
- Perform studies to evaluate the scale at which basin effects become of interest to typical nuclear facilities.
- Perform studies to evaluate the impact of 2D propagation of surface waves in areas with deep, stiff soil profiles (e.g., the Mississippi river embayment).
- Report the program results, including the full laboratory testing data set, constitutive model updating/development, case-history information and analyses, and results of all sensitivity and soil-structure interaction (SSI) analyses.

Deliverables

- Report(s) documenting the program results, including the full laboratory testing data set, constitutive model updating/development, case-history information and analyses, and results of all sensitivity and SSI analyses.
- Based on the program results, NRC staff will recommend and incorporate updates to NRC regulatory guides and the Standard Review Plan.

2.7 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 events) 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 present themselves when considering extreme ground motions in hazard analyses. These include:

- **The use of equivalent linear versus non-linear site response.** When are non-linear studies 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 aren't large enough to accurately assess 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 non-exceedance 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 funding has been used to initiate work in this area. As a result, the NRC has an opportunity to capitalize on this work to significantly improve hazard estimates at low probabilities through joint funding or support of targeted initiatives.
- **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 pre-instrumental period.
- **The effects of 2D and 3D loading (as discussed above).**

Tasks and Deliverables

Because this is a newly identified area of interest, the NRC staff is in the process of developing the scope of work and set of contractor deliverables in this area. This process will be a collaborative effort between RES, the NRC's Office of Nuclear Material Safety and Safeguards (NMSS), and other NRC seismic staff.

Based on the program results, NRC staff will recommend and incorporate updates to NRC regulatory guides and the Standard Review Plan.

2.8 Comparison of NUREG/CR-6728 Recommended Spectral Shapes to Other CEUS Attenuation Relationships

NUREG/CR-6728, "Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines," presented attenuation relationships and spectral shapes for use in developing and reviewing plant applications. However, the subsequent acquisition of extensive datasets of strong-motion recordings and the development of revised ground motion prediction equations indicate that it is appropriate (and advisable) to review the suggested spectral shapes presented in NUREG/CR-6728.

The first phase of this task involved comparing the NUREG/CR-6728 spectra with those determined from the latest data and attenuation functions. The results of that comparison indicated that the NUREG/CR-6728 spectra for the CEUS differed from the latest attenuation functions, but that there was not a strong technical basis for choosing the specific attenuation relationship used to update NUREG/CR-6728. As a result, the technical basis for the update of NUREG/CR-6728 needs to be developed. This effort will be coordinated with the NGA-East Project, looking at spectral shapes and attenuation functions in the CEUS. If revised spectral shapes appear to be appropriate, they will be developed along with standard time-histories based on any new relationships for a variety of magnitude and distance bins in a second phase of the project. Because of the reliance on products from the NGA-East Project, this work will be scheduled on the basis of the output from that project.

Tasks

- Compare NUREG/CR-6728 response spectra to new attenuation relationships and the expanded earthquake record database and determine if update is necessary (Phase 1).
- Document the decision to proceed to Phase 2 or the adequacy of existing NUREG/CR-6728 spectral shapes (Phase 1).
- Develop new CEUS response spectra based on updated attenuations relationships and the expanded earthquake record database, and develop a new contractor-prepared NUREG/CR -series report for industry use (Phase 2, if needed).
- Incorporate new response spectra into regulatory guidance (e.g., update current examples provided in Regulatory Guide 1.208) and the NRC's Standard Review Plan (SRP, NUREG-0800), as appropriate (Phase 2, if needed).
- Develop a new set of standard time-histories based on any new relationships for a variety of magnitude and distance bins (Phase 2, if needed).

Deliverables

- New contractor-prepared NUREG-series report detailing updated CEUS spectral shapes (Phase 2, if needed).
- Updated regulatory guidance and SRP (Phase 2, if needed).
- New sets of standard time-histories based on revised response spectra for a variety of magnitude and distance bins (Phase 2, if needed).

2.9 Development of Recommendations for Shape of Minimum Response Spectrum 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 and later updated slightly in Regulatory Guide 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe-Shutdown Earthquake Ground Motion." 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 comprised the database of recordings available at the time. Uniform hazard response spectra developed using new data and attenuation relationships predict that the standard design spectral values will be exceeded at high frequencies for many sites. Consequently, new standard design spectra more in line with current knowledge and the state-of-practice needs to be developed. Currently, there are thousands of earthquake records available, and new attenuation relationships based on this expanded database are now available for the 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 response spectrum to be used in the standard design of new plants and evaluation of existing NPPs and other nuclear facilities.

This work will be initiated after the results from the NGA-East program are obtained.

Tasks

- Review possible technical basis for development of new standard spectra that includes, but is not limited to, both the method used by Newmark and Hall to develop NUREG/CR-0098, "Development of Criteria for Seismic Review of Selected Nuclear Power Plants," and the assumed minimum earthquake method.
- Undertake analyses using the methods chosen for further study (above) and assess the impact of region and site type.
- Review the results from the analyses and determine which spectra (or combinations of spectra) should be adopted.

Deliverables

- The results of this work will be detailed in a NUREG-style report, which will form the basis for a new NRC regulatory guide. The results will also be incorporated into the Standard Review Plan

2.10 Analysis of Effect of the Cumulative Absolute Velocity (CAV) Filtering Approach on the Shape of the Probabilistic Hazard Curves

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 low-magnitude, short-distance earthquakes that have insufficient energy to cause damage to facilities from the sources included in the PSHA. 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 short time periods 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 43-05 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 1E-04 to 1E-05. The application of CAV filtering may have the effect that this assumption is no longer applicable, and, in fact, the value of the hazard curve at some return period 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 1E-4/year should be approximated as 45% of the value for the annual frequency of 1E-5/year. However, there is insufficient technical evidence to fully support this assumption, although it is assumed to be conservative.

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 1E-4/year level goes to zero. This work will be undertaken in consultation with the NRC’s Office of New Reactors (NRO) in order to meet specific regulatory needs that are anticipated to arise once CAV filtering comes into use.

Tasks

- Review the impact of CAV filtering on response spectra shape for those nuclear facility site submittals that have already been provided to the NRC.
- Investigate additional cases that may result in greater-than-average reduction in the calculated hazard at high spectral frequencies over long return periods of interest.
- For cases in which the calculated hazard value for the annual frequency of 1E-4/year hazard goes to zero in a PSHA as a result of an increase in the minimum magnitude used in the PSHA, analyze and validate the proposal to use 45% of the value for the annual frequency of 1E-5/year as an alternative minimum acceleration value to be used in design.

Deliverables

- Report detailing PSHA-based methods used in analyses undertaken, results obtained, and recommendations provided for either acceptance of the proposed method or alternative methods developed to address issues that arise when the power law assumption is not met.
- Based on the results of the research, NRC technical staff will develop recommendations for revision of NRC regulatory guidance and the Standard Review Plan. If research results differ significantly from previous assumptions, NRC staff may also develop a NUREG-style report.

2.11 Tsunami Hazard Evaluation

The Sumatran earthquake in December 2004 (magnitude ~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 close to 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 the USGS to review the existing state-of-knowledge for the tsunami hazard assessment, mitigation, and landslide mechanics. In May 2006, RES invited four NOAA and USGS scientists to brief the NRC’s Seismic Issues Technical Advisory Group (SITAG) on research and state-of-knowledge for both earthquake- and landslide-induced tsunamis. This meeting kicked off research efforts in the area of tsunami hazard assessment. As a first step, in October 2006, an advisory panel of tsunami experts from the USGS and NOAA provided a draft document summarizing the state-of-knowledge on tsunami hazard assessment for use in updating the SRP (NUREG-0800).

In addition, a long-term, multi-phase 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 was initiated in FY 2006. 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. This work is being undertaken by the USGS, and the sources identified include both seismic sources and submarine landslides. The draft database of tsunamigenic sources was delivered in May 2007 and finalized in September 2007. NRO plans to use this database in reviewing new applications on the East and Gulf Coasts. Specifically, NRO can compare the sources identified in the database to the assumptions detailed in the permit applications.

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 at the end of FY 2007. The USGS will continue with source investigation and analysis. The modeling work will be undertaken by NOAA 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 only of interest when considering long return periods (such as those considered for nuclear facilities). For this reason, very little research has been undertaken 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.

Tasks

- Collect and analyze existing data to be used to develop a preliminary database of tsunamigenic sources that may impact the East and Gulf Coasts of the United States (completed).
- Identify data gaps in the existing database, and develop a plan to address those gaps (completed).
- Use field techniques to acquire missing data, as identified.
- Using the existing and newly acquired data, update the preliminary database to develop a new database of tsunamigenic sources that may impact the East and Gulf Coasts of the United States. The database will include all characterizations appropriate for tsunami modeling.
- Perform tsunami hazard assessment modeling resulting in wave heights and draw-down off the coastline using the source database and state-of-the-art modeling. This may include both the offshore “linear” work for the whole of the East and Gulf Coasts and the near-shore “non-linear” work for a number of specified sites (to be performed by NOAA’s PMEL facility).
- Develop/identify guidelines, tools, and capabilities for near-shore non-linear run-up modeling. Use available coastal topographic and hydrologic models to develop the capability to develop site-specific inundation and run-up predictions. Compare in-house results to NOAA results for specific locations of interest, as needed.

- Investigate cutting-edge soil modeling techniques for use in determining the potential for tsunamigenic landslides in the East and Gulf Coasts based on near-shore site investigations. In the final stages, modeling capabilities would be developed in-house.
- Develop a long return period database of tsunamis and landslides for comparison with PTHA results and for use in estimating recurrence frequencies and magnitudes.

Deliverables

- Preliminary technical report that characterizes tsunami sources, including both remote and local seismic, landslide, and other sources, which can have wave impact on coastline nuclear facilities (Version 1 completed).
- Technical reports detailing investigations to acquire additional data, as needed.
- Final technical report that characterizes tsunami sources for the entire East and Gulf Coasts.
- Technical report that provides results of near-shore modeling for the East and Gulf Coasts of the United States. A goal of this report is a run-up and drawdown map for the coasts.
- Updated Regulatory Guide 1.59, “Design-Basis Floods for Nuclear Power Plants,” as necessary.

3 EARTHQUAKE ENGINEERING ANALYSES AND EARTHQUAKE-RESISTANT DESIGN

This section provides details regarding elements of the Seismic Research Program Plan that focus on either engineering analyses or earthquake-resistant design.

3.1 Random Vibration Theory-Based Site Response

Site response analysis methods are used to determine how the soil at a site responds to a ground motion of interest. Currently, site response analyses are conducted using equivalent linear methods, fully non-linear methods, and random vibration theory (RVT) based methods. All three methods are accepted by the NRC. Until recently, the use of RVT-based methods was limited in practice because (1) a limited pool of people were versed in the RVT-based methods, (2) there is no publicly available software that uses the RVT method, and (3) the RVT methods are highly detailed. Nonetheless, RVT-based methods are now being used for the development of ESP and COL applications because such methods are an efficient way of incorporating both the "Method 3" site response framework (described in NUREG/CR 6728) and the Cumulative Absolute Velocity (CAV) filtering technique that reduces high-frequency motions in the site-specific response spectrum.

Recent research results indicate that RVT methods may have a systematic bias which is conservative in the high-frequency range (up to the predominant period of the soil column) and an unconservative bias in the low-frequency range as compared to fully non-linear methods. The research discussed herein would extend an existing research program to site conditions and seismic hazard levels consistent with CEUS conditions. It would fund efforts to better understand the source of the systematic bias, to update the technique to remove the systematic bias, and to more clearly represent the sources of uncertainty.

The objective of this work is to support the regulatory activities of the NRO staff in three ways. Specifically, this research will help the staff (and industry) better understand and address uncertainties and systematic bias in the RVT-based methods of site response that are currently being used in the development of ESP and COL applications. This research will also provide the staff with guidelines and general technical support for reviewing applications using RVT-based site response analysis methods. In addition, this research will develop open-source numeric analysis tools to support independent review of applications using RVT-based methods.

This work was initiated at the end of FY 2007.

Tasks

- Develop a white paper discussing key technical areas that NRC staff should consider when reviewing or performing analyses that incorporate RVT methods. This white paper should provide both a summary of each topic and a discussion of the impact of analyst decisions on results.
- Perform analyses comparing equivalent linear, non-linear, and RVT site response analysis methods for generic soil profiles and hazard levels of interest to nuclear plants sited in the CEUS. The analyses should include three generic soil profiles and three levels of shaking per soil profile. Results and comparisons should be provided in terms of surface response spectra and amplification factors.
- Provide the RVT site response software used in the above analyses, develop software documentation for the NRC staff, and provide training on the software.

Deliverables

- White paper report documenting and discussing key technical areas that NRC staff should consider when reviewing or performing analyses that incorporate RVT methods.
- Report on results of analyses comparing equivalent linear, non-linear, and RVT site response analysis methods for generic soil profiles and hazard levels of interest to nuclear plants sited in the CEUS and provide advantages and disadvantages of each method.
- RVT-based site response software with documentation and training for NRC staff. This software will be used for independent review of applications that incorporate RVT analyses.
- RES staff will also support NRO in updating the relevant SRP sections or in developing interim staff guidance, as appropriate.

3.2 Analysis and Validation of New Proposed Site Response Methods

A variety of new methods have been developed for use in assessing the response of soil to seismic motions. An overview of these methods is provided in NUREG/CR-6728. Some of these methods are already being used in the development of new applications. However, it is not clear how the results of these methods compare with each other and with the true anticipated response. It is also not clear what the level of epistemic uncertainty is for different regions of the United States. This project is being undertaken to provide a strong and justifiable technical basis for regulatory decisions.

This project involves reviewing the proposed site response techniques and using specific and generalized case studies to examine and quantify the potential impact of each method. This work will be undertaken in consultation with NRO, in order to meet both specific and urgent needs, and to assess the need for improved regulatory guidance.

This work was initiated at the end of FY 2007 and is coordinated with related work that involves investigating the impact of CAV filtering (as previously described).

Tasks

- Summarize existing and proposed techniques used in site response analyses, including comparison of the methods and applicability of each method to the WUS and CEUS.
- Use case histories to compare the results of each method for a variety of sites.
- Develop internal guidance on the proposed site response techniques for NRC staff involved in reviewing new applications.

Deliverables

- Report documenting the analysis results and guidance to NRC staff for use in reviewing applications. This report will include information on the relative accuracy and issues related to each site response method. RES staff will also support NRO in updating the relevant SRP sections, as appropriate.

3.3 Review of Frequencies Used in Deaggregation of Hazards for Development of Controlling Earthquakes Used in Site Response Analyses

The NRC's regulatory guidance recommends that a minimum series of six controlling earthquakes be determined for use in site response and other analyses. Those six events represent the greatest hazard in the high- and low-frequency ranges for each of the annual frequency of exceedance levels. These earthquakes are currently identified based on deaggregation of hazards at two frequencies for each of the frequency ranges of interest (i.e., 1 and 2.5 Hz for the low-frequency ranges, and 5 and 10 Hz for the high-frequency ranges).

It is unclear whether there is a benefit to requiring deaggregation of hazards at the four frequency values noted above, or if the same information could be gained from using only two frequencies (i.e., 1 and 10 Hz). This project will investigate this question based on deaggregation of both existing/proposed plant locations and general site conditions. This work will be undertaken in consultation with NRO in order to meet specific NRO needs related to application reviews and to assess whether additional regulatory guidance should be provided in the future.

Tasks

- Perform a new PSHA or review PSHA results for existing and proposed nuclear facility locations. Deaggregate hazards at each frequency level of interest (1, 2.5, 5, and 10 Hz) for the annual frequencies of interest (e.g., 10^{-4}, 10^{-5}, 10^{-6}, and beyond).
- Review attenuation relationships for the various seismic regimes found in the United States to assess the cases, if any, in which using four spectral frequencies yields a different result than using two spectral frequencies.
- For cases where the use of two spectral frequencies has an impact on the results, characterize the range of potential impact.
- Summarize the results from the above tasks for internal review, and identify proposed future actions, if necessary.

Deliverable

- Internal report detailing the analyses undertaken, comparison of results using both the method detailed in Regulatory Guide 1.208 and alternative methods (alternative spectral frequencies), and recommendations for future updates to existing regulatory guidance (if appropriate).

3.4 Validation of the Proposed Coherency Methodology

As seismic waves propagate through bedrock and soil, they are scattered by geologic materials. When these waves reach a surface, such as a foundation, this scattering (along with wave passage effects) leads to a situation in which the traction forces imposed on the surface by the soil vary (i.e., are incoherent). The resulting response of a foundation to the seismic loading is diminished. This incoherency effect increases as the frequency content of the incoming wave increases.

In an engineering context, the term "coherency" connotes the degree to which two points in the soil are moving in phase at each frequency. Methods for incorporating incoherency effects into seismic design of nuclear facilities have been proposed by the industry. These proposals include both a Fourier spectrum-based coherency function and implementation of the function into the frequency-based SSI programs (i.e., SASSI and CLASSI). The implementation of a coherency function in accepted SSI programs is of great significance because it is the most effective way to address the issue of predicted motions in the high-frequency range that exceed the enhanced Regulatory Guide 1.60 spectrum used for some standard plant designs.

Although significant work has been undertaken to review the proposed methodology (under the current effort to develop Regulatory Guide 1.208 and updates to the related SRP), a fuller validation program is warranted. This work will be initiated at Lawrence Livermore National Laboratory (LLNL) in FY 2008.

In addition to the analyses discussed above, because current models were developed in data recorded at a single site, it would be of significant interest to the NRC to obtain additional data from new seismic arrays founded on rock sites. Although it is not appropriate for the NRC to independently develop a new hard-rock seismic array, opportunities to support or collaborate on new data sources may be appropriate for funding. This is particularly true if spacing is very small (5–19 meters) and the site consists of very hard rock (V_s>9200 feet/second). Obtaining data from additional locations would allow NRC staff to assess the level of aleatory variability across different sites versus at a single site.

Tasks

- Develop time-domain FE models to investigate effects of incoherency effects in two and three dimensions. The first model will mimic (as closely as possible) the frequency-domain model used in the SASSI analyses. The second, more robust, model will have sufficient detail to accurately capture key structural responses, including rocking and rotational motions.

- Review results of analyses detailed in the EPRI reports that were developed using the proposed changes to existing frequency-based programs (SASSI and CLASSI) that are widely used in industry, and compare results to those developed by FE modeling efforts.
- Develop internal guidance on use of coherency techniques.
- If possible, participate in research to obtain new strong motion array data on hard rock sites.

Deliverable

- Report detailing the analyses undertaken and comparing the results of time-domain analyses with results of analyses detailed in EPRI reports provided to the NRC staff.
- Because the use of the coherency function may increase the prediction of rotation and overturning response in a structure, NRC staff will develop a set of recommendations that detail locations and/or failure mechanisms that that should be analyzed during reviews for new NPP applications that incorporate the coherency function in their SSI analyses.

3.5 Analysis of Effects of Alternative Methods of Time-History Development on the Results of Site Response Analyses

A number of methods are currently used to develop the earthquake record time-histories that are used in design and analysis techniques. The choice of time-history selection and modification techniques can have significant impact on the results of both SSI analyses and the site response analyses used in determining SSE. A significant and focused discussion regarding the impact and value of the various methods is currently ongoing in the professional seismic hazard community. However, the current discussion tends to focus on spectral frequency ranges of interest only to typical construction projects and may not consider very high- or low-frequency ranges that are of interest to nuclear facilities.

This project will review state-of-the-art assessments and comparisons of existing methods of time-history development that are currently ongoing, explore the most promising methods in the full range of spectral frequencies of interest to the NRC using case histories, and develop guidance on methods deemed to be the most appropriate for nuclear facilities.

It is intended that the results of this work be made publicly available as a NUREG-series report. Given the significant current efforts to reach consensus on this topic in the professional seismic hazard community, and the valid concern that any guidance would soon be out of date, this issue was not addressed in developing Regulatory Guide 1.208. Rather, Regulatory Guide 1.208 carried over the method detailed in Regulatory Guide 1.165, which is still considered to be an acceptable method although it is no longer widely used in practice.

Tasks

- Review current state-of-the-art assessments, comparing existing methods for time-history development.
- Determine the most promising methods in the full range of spectral frequencies of interest to the NRC.

- Undertake analyses to develop the mean responses of single-degree-of-freedom (SDOF) systems from a large number of natural time-histories focused on a typical target response spectrum. Analyses will continue to be added until additional runs have no impact on the mean response.
- Undertake the number of SDOF analyses required to determine a stable predicted mean response for each of the identified methods.
- Compare the number of required analyses and accuracy of the mean response predicted by the various methods for each frequency of interest.
- Summarize results and develop both internal and external guidance on methods that produce the best results for the structural frequency range of interest to nuclear facilities. These results would likely result in a NUREG-series report.

Deliverable

- NUREG-series report of time-history development techniques and their impact on nuclear facility analysis results.

3.6 Investigation of Performance-Based Design Techniques in the Design of Structures, Systems, and Components of Nuclear Power Plants

With the recent publication of Regulatory Guide 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion", the NRC has incorporated performance-based seismic loading for new reactor designs. The seismic loading is used to develop the floor spectra that are used in the design and analysis of structures, systems and components (SSCs). However, while the seismic loading is calculated in a probabilistic performance-based framework, the design of SSCs currently uses a deterministic approach that does not take full advantage of the information gained during calculation of the input motion. This leads to a final design that is not truly performance-based or risk-informed. This project will investigate and analyze the impact of the use of deterministic methods in the design of NPP SSCs in term of calculated risk levels. It will also investigate methods for implementing performance-based techniques in NRC activities and approaches.

This research topic will include the use of integrated finite element modeling. As a result, the analyses result may be useful to investigate the topic of advanced and non-traditional fragility curves, an area of research which is starting to be of great interest in the broader seismic community. This interest has resulted from the increased understanding that the use of zero period acceleration (ZPA) or peak ground acceleration (PGA), the traditional ground motion parameter used for fragility curves, does not accurately predict damage for SCCs with longer natural periods. This project will use the result of the integrated modeling to investigate the use of alternate ground motion measures (e.g. the 0.3 and 1 second spectral accelerations, the cumulative absolute velocity, and the average acceleration over frequency ranges of interest) for possible future research.

Tasks

- Using simplified integration techniques, analyze the impact to overall risk of using deterministic design methods as compared to performance-based methods by assuming fragility curves of typical for key SSCs and integrating over probabilities of interest. Determine the types of fragility behavior that has the biggest impact on calculated risk.
- Review actual fragility curves (if available) or develop new fragility curves for key components of interest using advanced numerical methods (if not adequate or available).
- Using a robust time-domain simulation of a NPP, perform a series of non-linear analyses to determine the overall performance of SSCs for a range of loading levels consistent with typical values determined during deaggregation.
- Perform an advanced probabilistic risk assessment by integrating the hazard levels with calculated performance results.
- Investigate and consolidate information and results from ongoing research related to the complete integration of analyses of seismic hazard, soil and structural response, and system and component response.
- Considering best-practice methods used in the broader community, consolidate and discuss options for practical implementation of performance-based design and analysis methods for NRC staff.

Deliverables

- Develop a NUREG-style report that describes analyses results, discusses the ongoing research and techniques used in the broader community, discusses technical issues related for performance-based design of NPP SSCs, and provides recommendations related to the implementation of performance-based design and analysis of NPP SSCs.

3.7 Investigation of Service and Age Related Degradation of Structures and Passive Systems and Components

Over the last few years research has been undertaken in the NRC to consider the degradation of certain types of systems and components over time. An understanding of degradation of SCCs has been of particular importance as NPPs go through the re-licensing process. This research has occurred simultaneously with significant advances in structural health monitoring and non-destructive testing among the broader research community. For example, the understanding of aging and degradation of structures is being significantly improved through research programs that continually monitor the structural response of bridges to ambient and micro-seismic activity. This new field, called structural health monitoring, is growing rapidly and has significant potential to provide new information and insights for all types of structures. This technology can also be combined with non-destructive testing to meet the unique needs and goals of the NRC.

This research program will first investigate the possible uses of the new state-of-the-art tools and techniques to determine which may be of interest to the NRC and then implement a targeted research program to investigate the aging and degradation of important SCCs not previously investigated under typical loading conditions. The results of this research will not only allow us to more accurately assess the as-is state of existing SSCs, but will also help to assess the condition of plants after an event, such as an earthquake or flood. The importance of this capability was highlighted recently as a result of the recent earthquake at the Kashiwazaki-Kariwa power plant.

Tasks

- Collect and review existing information related to the degradation of materials that may provide insight in the degradation of SSCs of interest.
- Review existing information on non-destructive testing methods that have already been investigated by NRC staff.
- Collect and review information related to new state-of-the-art methods for structural health monitoring and investigate the potential for technology transfer to other systems and components.
- Collect and review information on any destructive testing that has been performed on systems and components of interest. Testing performed after exposure to heat, corrosive chemicals, or other adverse environments is of particular interest.
- Collect and review information on seismically induced damage in the Kashiwazaki-Kariwa Nuclear Power Plant
- Based on the above, develop a plan for a targeted research program to investigate the aging and degradation of important SCCs not previously investigated under typical loading conditions.

Deliverables

- White paper on the result of the investigations noted above
- Recommended plan, to be reviewed by knowledgeable NRC staff, for a targeted research program to investigate the aging and degradation of important SCCs.
- Because the results of this research are focused on understanding how components age overtime, this research will assist NRC staff in assessing the safety of aging plants using probabilistic risk assessments.
- The results of this research program will be detailed in a NUREG-series report, which can be used to update regulatory guidance on assessment of seismic capacity of existing and future plants.

3.8 Analysis of Seismological Basis for Loading Used in Shake Table Testing of Equipment Subjected to High-Frequency Ground Motions

Existing nuclear power plants have been designed using site-independent spectral shapes (i.e., Regulatory Guide 1.60 or NUREG/CR-0098) that have dominant spectral amplification in the 2–10 Hz range. In contrast, site-specific uniform hazard response spectra (UHRS) for CEUS site conditions have dominant spectral amplifications for frequencies greater than 10 Hz. Site-specific UHRS developed as part of recent ESPs and COLs have shown spectral values that exceed the standard Regulatory Guide 1.60 spectral shape for frequencies greater than ~10 Hz.

To evaluate the potential impact of the high-frequency spectral exceedances, a program of shake table testing of equipment is planned. An important input to this testing will be the development of appropriate acceleration time-histories to be used. This project will examine the seismological basis for selecting appropriate characteristics for time-histories to be used in the testing program.

This project will be initiated in FY 2008 if funding is available.

Tasks

- Perform hazard deaggregation for a range of site conditions and relevant hazard characteristics in terms of magnitude, distance, and epsilon.
- Based on the results of the first task (the relevant set of magnitude, distance, and epsilon values), develop a list of the important seismological characteristics, such as total duration, number of cycles, and high-frequency phase behavior that should be used to define the attributes for time-histories to be used in the testing program.
- Document the results of the above tasks in a white paper.

Deliverables

- White paper summarizing the hazard deaggregation study results and attributes that should be used to define time-histories to be used in the testing program.
- Based on the project results, NRC staff will recommend minimum input motions for testing of equipment subject to high frequency motions and updates to regulatory guidance that address the seismic qualification of equipment. NRC staff may also recommend changes to relevant IEEE standards.

3.9 Development of Guidance for Dynamic Analysis of Deeply Embedded Structures

Several advanced reactor designs propose to fully or partially embed reactor structures as one of their major features. The objective of this program is to develop the technical bases to support the NRC staff's evaluation of those proposed embedded structures.

Computer codes that are current used for SSI analysis in the nuclear industry have been developed for and applied to coupled soil-structure models where the structures are founded at or near the ground surface with shallow embedment. These computer codes have been developed to determine the seismic responses, such as amplified response spectra, forces, and moments, which are required for the detailed analysis and design of structures, equipment, and piping, considering the interaction between the soil and the structure during seismic events.

In February 2006, the NRC published NUREG/CR-6896, "Assessment of Seismic Analysis Methodologies for Deeply Embedded Nuclear Power Plant Structures." That report documents the research performed by Brookhaven National Laboratory (BNL) to investigate the applicability of existing seismic design practices and SSI computer codes to deeply embedded or buried structures. The BNL report concluded that the existing computer codes can be used for SSI response calculations for deeply embedded structures located in areas of low to moderate ground motions if the results are examined in detail by an experienced analyst. For deeply embedded structures located in an area of strong ground motion, additional ground motion data would enhance the capability of existing computer codes. Because it is difficult to obtain ground motion data, the staff plans to perform additional analytical studies, using non-linear computer codes to better simulate the strong ground motion.

Tasks

- Perform analytical studies, using non-linear computer codes, for deeply embedded structures located in areas of strong ground motion, and document the results in a NUREG-series report.
- Review regulatory guidance, including relevant regulatory guides and SRP Section 3.7.2, “Seismic System Analysis,” to identify changes that may be required for the analysis of deeply embedded structures based on the conclusions presented in NUREG/CR-6896.

Deliverables

- NUREG-series report documenting the results non-linear analyses of deeply embedded structures located in areas of strong ground motion.
- Memorandum to management recommending changes, if any, to regulatory guides and/or SRP Section 3.7.2.

3.10 Investigation of Lateral Earth Pressures on Foundation Walls and Floors During Seismic Events

The importance of seismically-induced (or dynamic) pressure on walls was recognized by Okabe (1924) and Mononobe (1929) following the great Kanto earthquake of 1923. This insight led them to develop the Mononobe-Okabe (M-O) method for determining seismically-induced lateral earth pressures on walls. Although decades have passed since the M-O method was developed, seismically-induced lateral earth pressures are still very poorly understood and very few predictive tools exist.

As a result, the M-O method is still the most widely used tool for predicting seismically-induced lateral earth pressure with finite element modeling used for advanced analyses. Unfortunately, lack of accuracy and precision is a significant issue. This is because the difficulties of obtaining actual field data and the complexity and cost of the necessarily large scale laboratory studies have combined to result in a problematic lack of data.

Accurate prediction of seismically-induced earth pressures are of interest for NRC staff because several advanced reactor designs propose to fully or partially embed reactor structures as one of their major design features. The lack of accurate tools to assess lateral seismic earth pressures will likely lead to significant uncertainties when NRC staff is faced with regulating the next generation of reactor. As a result, a initiating a program to investigate and develop tools and techniques to more accurately predict lateral earth pressures on foundation walls during seismic events is in the interest of NRC staff.

Tasks

- Collect and summarize the existing tools for predicting seismically-induced lateral earth pressure
- Collect and summarize existing field data and laboratory studies available and compile database. This may include data from centrifuge testing, shake table testing, and sensors installed at Reactor 6 of the Kashiwazaki-Kariwa power plant.
- Collect and summarize available finite element work that has been performed to assess seismically-induced earth pressures and review any comparisons to recorded data.
- Using finite element modeling, perform parametric studies that vary modeling and analytical details likely to impact dynamic soil response. Modeling details of interest may include: wall stiffness, end connection details, three-dimensional effects, soil-cement friction, constitutive model assumptions and properties, potential for volumetric compression, dynamic soil softening, soil plasticity and gapping potential, and others.
- The above parametric study should be designed to correspond to a well-documented case history if possible. A detailed comparison should be made between the results of the parametric study and the case history.

Deliverables

- NUREG-series report summarizing the results of the above research. This report should include a summary of background information collected, detailed description of case histories collected, results from the parametric study performed, detailed comparison of parametric study results and relevant case history, and any other information that may be of interest to NRC staff.
- Based on results detailed in the NUREG-series report, NRC staff will develop a series of recommendations to use in the revision of regulatory guidance and the Standard Review Plan.

3.11 Investigation and Analysis of Base Isolation Systems in Nuclear Power Plants

Although the base isolation system technology has been around for over a decade, the use of base isolation systems has only recently become relatively commonplace. This is a result of the good performance of these systems during actual large seismic events and a result of the system's ability to significantly reduce seismic loading on structures and contents. Recently there has been on-going discussion in industry and among NRC staff of the engineering benefits of using base isolation systems at new NPPs located in regions associated with high seismicity. There has also been significant discussion of using base isolation as a key component of future generations of advanced reactors. Because of the high likelihood that industry will propose the use of base isolation systems in the next generation of plant designs, NRC staff believes that research activities should be implemented over the next few years to look at the engineering implications of the use of base isolation systems.

Tasks

- Collect and review information related to the use of base isolation systems in NPPs internationally.
- Determine the likely implementation schemes that could be used in US NPPs for both the current and next generation of reactors.
- Using advanced soil-structure interaction modeling techniques, analyze the engineering and risk-related implications of using base isolation systems in US NPPs.
- Develop a NUREG-style report discussing technical issues and benefits related to implementation of base isolation systems in NPPs.

Deliverables

- NUREG-style report discussing technical issues and benefits related to implementation of base isolation systems in NPPs.

3.12 Development of New Post-Processing Tool for the PCARES Code

In the process of reviewing and evaluating NPP structure designs, the NRC staff identified the need for a tool that can quickly validate the SSI models and associated analyses received from various applicants. These submittals typically contain results from numerical studies performed using large, state-of-the-art structural computer programs, which are difficult to assess without significant time and effort. To address this need, BNL initially developed the CARES code during the 1980s, and the code has been upgraded several times (most recently in FY 2006).

The most recent update allows the user to account for uncertainty in the soil properties by using Monte Carlo simulations with a range of possible soil properties. This accounts for one contributor to uncertainty. However, the program can only average the Monte Carlo results over a single input earthquake record. Given the non-linear nature of soil, the natural variability in the earthquake records themselves is another very important contributor to uncertainty in the site response analysis results. The in-house site response capability needs to accommodate both the variability in soil properties and the use of multiple earthquake records.

An in-house project will be undertaken to develop a simple MATLAB-based post-processor to combine outputs from PCARES (each consisting of results from at least 60 Monte Carlo realizations) for multiple earthquake records. This post-processor will be useful to both RES (for use in the research detailed in Section 3.2) and NRO (for use in regulatory activities, such as in-house independent review of applications).

Although BNL could undertake the work to implement this capability directly into PCARES, the in-house development of a MATLAB-based post-processor increases flexibility and significantly reduces cost.

Tasks

- Develop a MATLAB-based post-processor to combine results from multiple runs using different input time-histories.

- Develop documentation on use of the post-processor for NRC staff.

Deliverables

- Post-processor for the PCARES program and associated documentation to assist NRC staff in efficiently using the PCARES program.

3.13 Seismic Analysis of Advanced Reactor Designs

The NRC staff expects to conduct the pre-application review of high-temperature gas reactor (HTGR) designs in the next few years. The staff's related research is aimed at developing an independent capability to evaluate the seismic integrity of the new and unique features of HTGR designs. This scope of work was developed as part of a broader research program that will be developed based on an office-wide assessment of the technical research needed to support HTGR reviews and licensing that is being spear headed within RES. An additional program of this type for the Evolutionary Pressure Reactor (EPR) is also being developed. While it is not expected at this time that EPR-based research will be proposed as part of the Seismic Research Program Plan, a full review of regulatory requirements has not yet been undertaken.

In the research effort to develop independent seismic and structural analysis models of the reactor vessel internals and core support structures, the staff will evaluate the assumptions and limitations of the existing computer codes to assess their applicability to non-linear configurations, such as the non-ductile graphite core reflectors and core support structures for the HTGR design. In addition, the staff will review research studies performed by foreign research and development (R&D) organizations and regulators to assess their applicability to the NRC's needs.

In particular, the NRC plans to conduct research on the non-linear static and dynamic structural analysis of advanced reactors with long fuel tubes and core support structures for which the seismic margin might be controlled by the fuel design. For the HTGR-type plants, fuel pebbles are piled into a tall configuration, resulting in non-linear responses during horizontal and vertical components of earthquakes. Linear and non-linear elastic and plastic stress analyses should be performed for seismic and dead loads, taking into account contact stresses between the spherical pebbles within the tall piles of fuel pebbles. This work is currently focused specifically on the Pebble Bed Modular Reactor (PBMR) category of HTGRs.

Seismic margin studies for HTGRs will also enable the staff to determine the level of earthquake below which core damage is unlikely. This level of earthquake is called the plant's high-confidence-low-probability-of-failure (HCLPF) capacity. Because much credit is given to the integrity and quality control of the coated fuel pebbles to retain the radioactivity in the PBMR design, it is important to conduct research to determine whether the plant's seismic HCLPF capacity is controlled by the HCLPF of the fuel.

The staff also plans to conduct research to evaluate the effect of modular construction on the seismic response of HTGR-type plants. In a multi-module PBMR plant, the nuclear island consists of several modules constructed at various stages and placed on a common foundation mat.

The seismic capacity and seismic response of the plant, therefore, would depend upon its overall foundation size and interaction among the various modules. In addition, research is planned to confirm the minimum separation needed between modules to account for seismic events.

Tasks

- Review research performed by foreign R&D organizations and regulators; conduct independent research to develop seismic and structural analysis models of the HTGR-type reactor vessel internals and core support structures; and evaluate the assumptions and limitations of existing computer codes to assess their applicability to non-linear configurations.
- Perform linear and non-linear elastic and plastic stress analyses of PBMR vessel fuel tubes and core support structures.
- Determine seismic margins of the HTGR-type design and fuel to determine the HCLPF, and confirm that plant's seismic HCLPF capacity is controlled by the HCLPF of the fuel.
- Conduct research to evaluate the effect of modular construction, determine the seismic capacity and response of multi-module PBMR-type plants, and determine the minimum separation needed between modules to account for seismic events.
- Prepare a NUREG-series report documenting the details and results of the previous four tasks, including recommendations for any changes to existing seismic licensing criteria to account for the advanced reactor designs. This report will be part of a larger series resulting from the broader HTGR research plan.

Deliverables

- NUREG-series report (as described above).
- Research information letter (RIL) on staff recommendations.

3.14 Seismic Analysis of Dams, Levees, and Other Water-Retaining Structures

In the years since the failure of the levees around New Orleans during Hurricane Katrina, significant new efforts have been initiated to review the seismic analyses of dams and levees in other areas. In particular, the western states of California, Oregon, and Washington are initiating significant research efforts to assess the safety and risk of their local dams and levee systems. These efforts are likely to lead to new techniques and tools for analysis, as well as a new understanding of the risk posed by these structures.

Although the NRC does not currently have plans to update its regulatory guidance or reassess the water-retaining structures associated with existing nuclear facilities at this time, the staff should remain abreast of ongoing research in this area and provide appropriate information to other interested staff as it becomes available.

4 INTERNATIONAL COOPERATIVE RESEARCH ACTIVITIES

The NRC routinely engages in cooperative research activities with the International Atomic Energy Agency (IAEA), the Organization for Economic Cooperation and Development (OECD) and its Nuclear Energy Agency (NEA), and other organizations to foster the international exchange of data and analysis results, which contribute to the safe worldwide operation of nuclear facilities. In addition to ongoing activities, the recent earthquake impacts to the Kashiwazaki-Kariwa (K-K) Nuclear Power Plant provide a unique case history and opportunity to assess the accuracy of analytical tools that are typically used in designing NPPs and other nuclear facilities.

4.1 IAEA Extra-Budgetary Program on Seismic Hazard

In February 2007, IAEA staff presented participants [from Japan, Finland, France, European Commission Joint Research Centre (EC/JRC), Pakistan, and Switzerland] with a proposal for an Extra-Budgetary Project (EBP) for the seismic safety of existing NPPs. That proposal was based on a preliminary document that was previously prepared by the IAEA and a group of Japanese utilities led by TEPCO. Since that time, strong earthquakes have been recorded showing high peak acceleration values and triggering concern about the seismic safety of existing nuclear facilities. There is particular concern about how plants respond to an event that may exceed the original design-basis values. Newly defined seismic hazard estimates (particularly those developed using a probabilistic approach) are much higher than the original design bases, and seismic risk has become an important contributor to the total risk of the plant. In addition, an effort to define lessons learned at the K-K Nuclear Power Plant has recently been added to the project.

The objective of the proposed EBP will be to investigate available methods and practices for resolving the identified seismic safety issues affecting design and operational aspects of existing NPPs, and to provide advice for supporting Member States in their specific applications. The results obtained from the proposed EBP will also assist in the application of the recommendations and guidelines provided in related IAEA safety guides, as well as provide input for their revision.

The following topic areas are to be addressed under the EBP:

- Area 1: Reassessment of the seismic hazard
- Area 2: Reevaluation of the seismic safety of existing NPPs
- Area 3: Post-earthquake plant operational response
- Area 4: Databases on earthquake experiences.
- Area 5: Lessons learned in the K-K Nuclear Power Plant

The deliverables of the project will be technical documents (IAEA TECDOCs) compiling all material discussed during the project activities and providing specific, detailed guidelines and recommendations on the related issues, areas, and topics. A final report (also a TECDOC) will be issued to summarize the project's final results and achievements.

The NRC will benefit from participating in this program in several ways. First, this program is the key mechanism by which TEPCO plans to release data recorded during the July 2007 Earthquake near the K-K Nuclear Power Plant. Participation in the EBP provides both the best chance of obtaining the data and a link to Japanese researchers who can provide additional information about the plant's design and properties that NRC staff will likely need. In addition, this EBP provides and avenue to collect other information of interest to NRC staff, such as experience with degradation of SSCs in other countries and techniques for improving post-disaster response. Lastly, the topic of reassessment of seismic hazard is currently an area of significant interest among the international community and NRC staff. Participation in the program will help NRC staff resolve significant issues that have arisen related to the application of NRC methods globally.

4.2 Collaborative Seismic Research with Japan on Lessons Learned at the Kashiwazaki-Kariwa Nuclear Power Plant

In addition to the IAEA EBP on Seismic Hazard discussed above, TEPCO representatives have expressed interest in working directly with NRC staff on analysis of data recorded during the July 2007 earthquake. There may be some benefit to a direct collaborative relationship if the IAEA EBP does not address all the needs and interests of the NRC. Program plans can be developed in conjunction with the IAEA EBP on seismic hazard as is appropriate.

4.3 IAEA Extra-Budgetary Program on Tsunami Hazard

The Sumatran earthquake in December 2004 (magnitude ~9) and the associated devastating Indian Ocean tsunami have focused considerable global attention on critical structures and facilities that are sited on or close to the coastline. As a result, Japanese researchers and the IAEA have joined together to initiate an IAEA EBP on tsunami hazard, which is focused on sharing tsunami hazard assessment tools across nations.

This project has been developed around the task of performing tsunami hazard assessment for developing nations using modern tools developed by advanced nations (particularly Japan and the United States).

Participation in this project benefits the NRC by providing staff with Japanese modeling tools and analyses methods that may be useful as simple in-house first order approximation tools that can be used in areas impacted by the Cascadia Subduction Zone or the Carribean Subduction Zones. In addition, because the project will be assisting Member States in applying these tools to their coastlines and comparing the results to historic events, NRC staff will gain an understanding of the accuracy, uncertainty, benefits and drawbacks of the simplified tools.

4.4 IAEA Program to Update Hydro-Meteorological Guidance to Include Tsunami and Global Warming

In conjunction with the IAEA EBP described above, a small group of consultants have been asked to assist the IAEA in updating its flooding guidance, including expanding the guidance on tsunami hazard. This guide, entitled "Hydrological and Meteorological Hazards in Site Evaluation for Nuclear Installations," essentially merges the existing documents NS-G-3.4 and NS-G-3.5, with the following stated objectives:

- Take account of the recently gained flood-related knowledge and experiences of Member States and provide up-to-date guidance for site evaluation of hydrological and meteorological hazards. This update will utilize the insights gained by feedback from Member States, other organizations, and lessons learned from the IAEA safety review services.
- Update guidance to include recent findings and knowledge related to climate change.
- Merge Safety Guides NS-G-3.4 and NS-G-3.5 in order to streamline agency guidelines.
- Include hazard effects that were not included in the current version, such as the lowering of water levels.
- Expand the scope of the safety guidance to nuclear installations, other than NPPs, in order to provide coherent and comprehensive guidance.

Participation in this project benefits NRC staff by providing information and technical content developed by international experts that can be used in the revision of Regulatory Guide 1.59. The consultants will focus on developing a new chapter describing best international practice for assessing the impacts of tsunami. In addition, because the consultants working on this project include members of the Intergovernmental Panel on Climate Change, NRC staff will gain key information on how to incorporate the effects of climate change on flooding estimates into Regulatory Guide 1.59.

Tasks

- Develop a Document Preparation Profile for the IAEA Steering Committee (completed).
- Attend a consultants' meeting to prepare the first draft of the guide (February 2008).
- Attend a second consultants' meeting to prepare the updated draft guide to be forwarded for comments (May 2008).
- Attend a third consultants' meeting to incorporate Member States' comments into the final guide (May 2009).

Deliverables

- Updated IAEA document NS-G-3.5, "Hydrological and Meteorological Hazards in Site Evaluation for Nuclear Installations."

4.5 Collaborative Seismic Research with Japan on Large Scale Testing and Analysis

In August 1999, the NRC signed a 5-year collaborative agreement with the Japanese Agency for Natural Resources and Energy (ANRE), Nuclear Power Engineering Corporation (NUPEC). The collaboration continued (and was extended for an additional 5 years, expiring in August 2009) with the NUPEC successor, known as the Japan Nuclear Energy Safety Organization (JNES).

The research conducted and in-kind information exchanged under this collaborative agreement will leverage NRC resources to obtain technically sound earthquake test data for scale-model structures, multi-axial shear walls, piping, and equipment fragility tests as a basis for the agency's regulatory decisions. Toward that end, JNES will provide the test data and actual earthquake data, and the NRC will perform a detailed analysis of the test data. Since its inception, collaboration with JNES has proven to be a very economical way for the NRC to obtain the results of large-scale test programs that are not available anywhere else in the world. In addition, this research program provides opportunities to interact and exchange information with other Japanese organizations, thereby ensuring that the NRC staff remains cognizant of all ongoing seismic research in Japan.

The goal of this project is to better understand the seismic behavior of NPP structures and components, obtain large-scale seismic test data to benchmark analytical techniques, and confirm current seismic design and analysis methodologies. The current program ends in 2010. However, as long as Japan continues to invest in seismic engineering research, it is very beneficial for the NRC to continue its collaborative agreement with Japan to leverage the agency's resources and obtain technically sound earthquake test data.

Tasks

- Evaluate results of tests performed by JNES on three scale-model reinforced concrete (RC) structures (representative of boiling- and pressurized-water reactor buildings) at the Black Thunder Coal Mine site in Wyoming. The purpose of these tests is to study the non-linear SSI of the structures when subjected to peak ground accelerations ranging from 0.25g to 1.5g. Perform seismic analyses of the scale-models and surrounding soil, and compare the results with the test data supplied by JNES. Prepare a NUREG-series report to document the details of the test program, as well as the pretest and post-test analyses. This report will provide input for revision of the SRP and/or regulatory guide for SSI analysis for NPP structures, and will supplement the SSI-related information provided in NUREG/CR-6896 by providing the results of additional test data.
- Perform an analysis of multi-axial loaded shear walls, compare the results with test data supplied by JNES, and prepare a NUREG-series report to document the test and analysis results and provide recommendations for use in assessing the seismic capacity of RC shear walls.
- Prepare a NUREG-series report to document ultimate strength piping tests and analyses, and assess the provisions of the Boiler and Pressure Vessel Code by the American Society of Mechanical Engineers (ASME), as well as current methods for predicting elasto-plastic response and margins in piping systems.
- Prepare a NUREG-series report to document the testing and analysis of degraded piping and components, which will supplement the degraded piping and component data used in the NRC's work to predict seismically-induced loss-of-coolant accident (LOCA) frequencies.
- Prepare a NUREG-series report to document the assessment of the results of the equipment fragility tests performed and reported by JNES, and review the impact of those test results on the NRC's probabilistic risk assessment (PRA) program.

Deliverables

- NUREG-series report for the scaled model structures test program, and the related pretest and post-test analyses.
- NUREG-series report for the multi-axial shear wall test, including analysis of the test data, and recommendations for use in assessing the seismic capacity of RC shear walls.

- NUREG-series report for the ultimate strength piping tests and analysis of the test results.
- NUREG-series report for testing and analysis of degraded piping and components; this report will assess the impact of these results on the current database.
- NUREG-series report for the equipment fragility tests, including the impact on the NRC's PRA program.
- Research Information Letter (RIL) to describe the significant conclusions in the NUREG reports listed above and wrap-up the findings from the current collaborative agreement.

4.6 Committee on the Safety of Nuclear Installations (CSNI)

The staff participates in international technology exchanges through the IAEA Engineering Safety Section and the Seismic Subgroup of the Working Group on Integrity of Components and Structures (IAGE), under the auspices of the OECD/NEA Committee on the Safety of Nuclear Installations (CSNI).

Specifically, the mandate for the Seismic Subgroup encompasses the following responsibilities:

- Exchange views on generic technical aspects of seismic behavior of SSCs.
- Review, as necessary, national and international programs concentrating on research, operational aspects, and regulation.
- Stimulate new research and recommend possible international cooperative projects in the relevant technical areas.
- Develop common technical positions on specific seismic integrity issues and identify areas where further work is needed.
- Discuss the potential impact of seismic events on the safety, regulation, and operability of NPPs.
- In addition, in the Earth Science area, the NRC is participating in an IAEA Coordinated Research Project (CRP) on "The Safety-Significance of Near-Field Earthquakes." The organizing committee is currently finalizing an IAEA technical document (TECDOC) to formalize the procedures and technical details used in the CRP. Publication of the TECDOC is in the near future.

Tasks

- Participate in annual IAGE Seismic Subgroup meetings for technology exchange among member countries.
- Participate in the IAEA CRP on the Safety-Significance of Near-Field Earthquakes.

Deliverables

The NRC's international cooperative research activities will produce proceedings from OECD/NEA-sponsored workshops, as well as topical reports, as follows:

- Experimental Facilities for Earthquake Engineering Simulation Worldwide
- Apparent Discrepancies Between Nuclear and Conventional Seismic Standards

- OECD/NEA Workshop on the Engineering Characterization of Seismic Input
- The Relationship Between Seismological Data and Seismic Engineering
- Seismic Input Motions, Incorporating Recent Geological Studies
- IAEA TECDOC on the Safety-Significance of Near-Field Earthquakes
- Report on lessons learned by the NRC from a series of three workshops on seismic ground motion sponsored by the IAGE Seismic Subgroup

4.7 Participation in SMART-2008 Seismic Benchmark

Reinforced concrete (RC) buildings exhibiting 3D (i.e., torsion) effects and non-linear response are a primary concern in the field of earthquake research and regulation. In order to assess the capability of the structure to withstand earthquake loads as well as the impact of seismic loads induced on the contents, a scale model of an RC building with 3D effects will be tested in 2008 on the AZALEE shaking table of the Commissariat à l'Énergie Atomique (CEA) in Saclay, France.

The SMART-2008 Project (Seismic Design and Best-Estimate Methods Assessment for RC Buildings Subjected to Torsion and Non-Linear Effects) is supported by CEA and Électricité de France (EDF). A blind prediction contest is open to teams from the practicing structural engineering, academic, and research communities. Financial support to the CEA is not required for participation in this project.

The aim of the SMART-2008 project is to compare and validate approaches used for dynamic response evaluation of RC structures subjected to earthquakes and exhibiting both 3D (i.e., torsion) and non-linear behavior, including evaluation of loads induced to internal equipment, to quantify margins in design methodologies and to carry out realistic methods to quantify variability in order to produce fragility data. For this purpose, a 1/4 scale model of a three-story building with torsional effects (representative of a nuclear building) will be built and tested on CEA's AZALEE shaking table. The project is divided into two phases, including the blind prediction contest and the variability quantification and fragility assessment.

Tasks

- Develop a finite-element model (FEM) of the 1/4 scale model of the three-story RC building, and analyze the model to determine blind predictions of the response of the structure when subjected to the input seismic test motions provided by CEA/EDF. The seismic input motion will be a single time-history in each horizontal direction.
- Assess the test results provided by CEA/EDF, and improve the FEM model, as needed, to better match the predicted response of the structure with the actual recorded seismic input test motions. Participate in Synthesis Report meetings in March 2008 and February 2009.
- Using the improved analytical model developed in Task 2, perform variability quantification and fragility assessments based on the guidance provided by CEA/EDF. Participate in the Synthesis Report meeting in May 2010.
- Prepare a final report for the project summarizing all results developed as a result of the participation in the project and the conclusions from the project. Participate in the final technical workshop in October 2010.

Deliverables

- NUREG-series report documenting the results of the 3-D and non-linear analyses of the three-story RC model subjected to seismic excitation in the SMART-2008 seismic benchmark and detailing the participation and lessons learned from the benchmark.
- Memorandum to management recommending changes to regulatory guides and/or SRP based on lessons learned from the benchmark.

5 REGULATORY GUIDE UPDATES

In preparation for new NPP applications, the NRC is revising or developing approximately 480 draft and final regulatory guides. The staff categorized the regulatory guides into groups. The first group (Phase 1) represented the high-priority guides, which the staff updated by March 2007. Regulatory guides included in the previous version of this Seismic Research Program Plan, which are now completed, include Regulatory Guide 1.29, "Seismic Design Classification"; Regulatory Guide 1.208, "A Performance-Based Approach To Define the Site-Specific Earthquake Ground Motion"; and Regulatory Guide 1.61, "Damping Values for Seismic Design of Nuclear Power Plants."

The staff then prioritized the remaining regulatory guides on the basis of information from several sources. The regulatory guides discussed below represent those scheduled for updating or development in Phases 2 and 3. The objective of the program is to have all NRC regulatory guides updated by December 2009.

5.1 Revision of Regulatory Guide 1.100, "Seismic Qualification of Electric and Mechanical Equipment for Nuclear Power Plants"

Published in June 1988, Revision 2 of Regulatory Guide 1.100 endorsed the procedures that the Institute of Electrical and Electronics Engineers (IEEE) documented in its IEEE Std. 344-1987, "IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations." (The current version of that standard, IEEE 344-2004, was issued in 2005.) In addition, ASME plans to issue a revision of QME-1-2002, "Qualification of Active Mechanical Equipment Used in Nuclear Power Plants," by early 2007, to address both seismic and functional qualification of active mechanical equipment. The NRC will revise Regulatory Guide 1.100 to endorse IEEE 344-2004 and ASME QME-1-200X, with exceptions and clarifications as necessary, to describe acceptable methods of seismic qualification of electrical equipment, and seismic functional qualification of mechanical equipment in NPPs.

Tasks

- Review and evaluate IEEE 344-2004 to establish the NRC's related regulatory positions in Regulatory Guide 1.100.
- Review and evaluate ASME QME-1-200X to establish the NRC's related regulatory positions in Regulatory Guide 1.100.
- Revise Regulatory Guide 1.100 and issue the draft Revision 3 for public comment.
- Resolve public comments on the draft Revision 3, and issue the final guide for use.

Deliverables

- Draft Revision 3 of Regulatory Guide 1.100 for public comments.
- Final Revision 3 of Regulatory Guide 1.100 for use.

5.2 Revision of Regulatory Guide 1.122, "Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components"

The NRC published the current revision of Regulatory Guide 1.122 (Revision 1) in February 1978. As its title implies, this regulatory guide discusses the development of seismically induced motion in a structure. This motion is described in terms of floor response spectra, which are used for analysis and design of SSCs in NPPs and other nuclear facilities. The existing guide was developed before modern analysis tools became commonplace. As such, the guide would benefit from complete revision and should be redeveloped to incorporate the risk-informed and performance-based framework of ASCE 43-05 to be consistent with the recent revision of Regulatory Guide 1.208.

Because of the extensiveness of the revision and its potential impact on seismic design of NPPs, it would be beneficial to coordinate a research review group composed of both NRC staff and outside experts.

The update to Regulatory Guide 1.122 will be finalized by Mid-2009.

Tasks

- Form a research review group.
- Develop the draft Revision 2 of Regulatory Guide 1.122 for submission to the research review group.
- Iteratively incorporate comments from the research review group into Regulatory Guide 1.122.
- Revise Regulatory Guide 1.122 and issue the draft Revision 2 for public comment.
- Resolve public comments on the draft Revision 2, and issue the final guide for use.

Deliverables

- Draft Revision 2 of Regulatory Guide 1.122 for comment by research review group.
- Draft Revision 2 of Regulatory Guide 1.122 for public comment.
- Final Revision 2 of Regulatory Guide 1.122 for use.

5.3 Revision of Regulatory Guide 3.17, "Earthquake Instrumentation for Fuel Reprocessing Plants"

Published in February 1974, Regulatory Guide 3.17 describes the earthquake recording instrumentation that the NRC staff considered acceptable for the purpose of determining the seismic response of fuel reprocessing plant features important to safety. The current guide predates the development of digital instrumentation, and recognition of the importance of free-field instrumentation for analysis of SSCs and the need for validation of SSI and structural models. The update to this guide will include guidance for the placement of instrumentation near and within fuel reprocessing facilities and the characteristics of modern digital seismic instrumentation that is acceptable to NRC staff. The update will be coordinated with the update of Regulatory Guide 1.12, "Nuclear Power Plant Instrumentation for Earthquakes," and will be informed by the performance of seismic instrumentation in the recent earthquakes in Japan (lessons learned). Close interaction with NMSS staff will be needed to ensure that appropriate plant characteristics are assumed.

<u>Tasks</u>

- Using several simple structures designed to replicate the principal behaviors of fuel reprocessing plants, perform SSI analyses for a series of generic site profiles to determine the distance from the foundation at which motions can be considered to be "free field."
- Review and evaluate the state-of-the-practice in strong-motion seismic instrumentation, with particular emphasis on the shortcomings demonstrated by recent earthquakes in Japan. Consult with staff from the USGS National Strong Motion System, Consortium for Strong Motion Observation Systems (COSMOS), U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and California Strong Motion Program to develop insights into performance, cost, and reliability of available strong motion recording systems.
- Revise Regulatory Guide 3.17 and issue the draft Revision 1 for public comment.
- Resolve public comments on the draft Revision 1, and issue the final guide for use.

<u>Deliverables</u>

- Draft Revision 1 of Regulatory Guide 3.17 for public comment (2008).
- Final Revision 1 of Regulatory Guide 3.17 for use.

5.4 Revision of Regulatory Guide 1.12, "Nuclear Power Plant Instrumentation for Earthquakes"

The NRC published the current revision of Regulatory Guide 1.12 (Revision 2) in March 1997. This regulatory guide discusses the seismic instrumentation (e.g., seismometers and seismographs) requirements for new NPPs. Instrumentation in plants is a topic of interest and ongoing discussion between NRC staff and industry representatives. In addition to discussions with industry, the relatively poor performance of instrumentation in the Kashiwazaki-Kariwa Nuclear Power Plant during the July 2007 earthquake has made seismic instrumentation a key concern for NRC staff.

In support of this guide, a small research program has been organized to develop the technical basis for guidelines for free-field instrumentation. This research program will perform simplified analyses using typical plant and soil properties to determine the distance from the plant at which motions can be considered to be free-field in nature.

Because this guide is closely tied to Regulatory Guide 1.122, discussed above, the research review group composed of both NRC staff and outside experts to be coordinated in support of the revision of Regulatory Guide 1.122 may be asked to also review the revision of this guide.

The update to Regulatory Guide 1.12 will be finalized by mid-2009.

Tasks

- Develop the draft Revision 3 of Regulatory Guide 1.12 for submission to research review group (if appropriate).
- Iteratively incorporate comments from research review group into Regulatory Guide 1.12.
- Revise Regulatory Guide 1.12 and issue the draft Revision 3 for public comment.
- Resolve public comments on the draft Revision 3, and issue the final guide for use.

Deliverables

- Draft Revision 3 of Regulatory Guide 1.12 for comment by research review group (if appropriate).
- Draft Revision 3 of Regulatory Guide 1.12 for public comment.
- Final Revision 3 of Regulatory Guide 1.12 for use.

5.5 Revision of Regulatory Guide 1.198, "Procedures and Criteria for Assessing Seismic Soil Liquefaction at Nuclear Power Plant Sites"

The current version of Regulatory Guide 1.198, published in November 2003, provides guidance to license applicants regarding acceptable methods for use in evaluating soil liquefaction potential at NPP sites. The technical basis for the current version is contained in NUREG/CR-5741 (March 2000), which outlines a deterministic assessment process. Since 2003, however, new state-of-the-art probabilistic methods and tools have been developed that have become common practice in most of the United States. Consequently, Regulatory Guide 1.198 requires revision, as it does not reference the most recent research, and its deterministic approach is inconsistent with a performance-based regulatory process.

<u>Tasks</u>

- Conduct a workshop to summarize the most recent advances in site characterization, laboratory testing, and analytical and empirical procedures for use in assessing liquefaction potential.
- Conduct research to assess the probability of liquefaction that is acceptable for use with certified designs that specify "no-liquefaction" in terms of a risk-based framework. This will resolve issues related to inconsistencies between the current certified design specifications (which allow plants on types of soils that could potentially soften, given sufficient shaking) and the state-of-the-art probabilistic tools.

<u>Deliverables</u>

- Draft Revision 1 of Regulatory Guide 1.198 for public comment.
- Final Revision 1 of Regulatory Guide 1.198 for use.

5.6 Revision of Regulatory Guide 1.138, "Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants"

The present version of Regulatory Guide 1.138 was published in 2003 and provides guidance to license applicants on acceptable methods for the evaluation of the engineering properties of soil and rock samples collected at potential at Nuclear Power Plant sites. One factor in the decision to update this guide is because the guide endorses ASTM 4015 (RCTS test standard), while newer, more advanced methods are preferred by NRC staff. As part of this work, a thorough assessment of the methods detailed in the regulatory guide as they compare to state of practice and state of the art techniques will be made.

<u>Tasks</u>

- Review the technical content of Regulatory Guide 1.138
- Develop consensus opinion of NRC staff regarding proposed changes to the guide.
- Update Regulatory Guide 1.138 and provide draft guide to public for comment.
- Incorporate public comments into Regulatory Guide 1.138 and publish for use.

Products

- Draft Revision of Regulatory Guide 1.138 for Public Comment
- Final Version of Regulatory Guide 1.138 for use