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USNRC RESEARCH AND REGULATORY GUIDANCE FOR SOIL-STRUCTURE INTERACTION

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SUMMARY

Over the last three years, the U. S. Nuclear Regulatory Commission (NRC) has focused attention on soil-structure-interaction (SSI) issues in order to better understand emerging issues and to update its regulatory guidance in regards to SSI. NRC's recent work is in advance of possible construction of new nuclear power plants (NPP) in the United States. Some conceptual designs for new NPP, also called advanced reactors, have proposed certain safety related NPP structures that will be partially or completely embedded below grade. In addition to this and other design features, some siting analyses for new NPP have used a performance-based method to determine the safe shutdown earthquake (SSE) ground motion. The performance-based method uses a target annual probability [e.g., 10^{-5} /year for the onset of significant inelastic deformation of systems, structures, and components] for the maximum acceptable facility damage from an earthquake. This paper presents some of the key areas that have been the focus of NRC activity over the last three years, namely: 1) the development of computational tools; 2) an assessment of deeply embedded structures and; 3) exploration of emerging issues; for example, performance-based methods and inclusion of seismic ground motion incoherency into SSI analyses.

INTRODUCTION

General Design Criteria (GDC) 2, "Design Bases for Protection Against Natural Phenomena," of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 Code of Federal Regulations (CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities," and GDC 4, "Environmental and Dynamic Effects Design Bases," of Appendix A to 10 CFR Part 50, require, in part that structures, systems, and components (SSCs) be designed to withstand the effects of natural phenomena, and to accommodate the effects of, and be compatible with the environmental conditions, associated with normal operation and postulated accidents. Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants," to 10 CFR Part 50, gives, in part, requirements for the implementation of GDC 2 with respect to earthquakes and soil-structure interaction (SSI). The NRC staff has recently reviewed a number of existing facilities and proposed new advanced reactor systems that require the development of in-structure response spectra through SSI response analyses. These response spectra are required for review of NPP design against the cited regulations and the Standard Review Plan (SRP) [Ref. 1]. The SRP is documentation of specific elements that the NRC staff consider when reviewing

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applications. The SRP is designed to work in conjunction with regulatory guides, which provide a broader and more general description of a topic.

In addition to the regulations cited above the staff has issued regulations for Early Site Permits (ESP). The ESP allows for a limited work authorization to perform non-safety site preparation activities, subject to redress, in advance of issuance of a combined license. Over the last three years the staff has reviewed applications for ESP under 10 CFR Part 52, Subpart A and associated siting evaluation criteria from 10 CFR Part 100.23, “Geologic and seismic siting criteria.” Regulatory guidance for the implementation of 10 CFR Part 100.23 for these ESP applications was provided in Regulatory Guide 1.165, “Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion,” (RG 1.165) [Ref 2]. More recently, March 2007, Regulatory Guide 1.208, “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion," (RG 1.208) [Ref 3] was issued to provide acceptable methods to meet these requirements.

RG 1.165, developed in the early 1990s, specifies a reference probability for exceedance of the safe shutdown earthquake ground motion (SSE) (i.e., seismic hazard, at a median annual value of 10^{-5}). This reference probability value was based on the average annual probability of exceeding the SSEs for 29 CEUS nuclear power plant sites and is used to establish the SSEs for future nuclear facilities. Preliminary results from a recent (2004) letter report from the United States Geological Survey (USGS) indicate that the reference probability for the 29 Central and Eastern United States (CEUS) sites is now about 6 to 7 x 10^{5}. This increase in the reference probability value is primarily due to recent developments in the modeling of earthquake ground motion in the CEUS.

Until recently no new applicants had applied for a Construction Permit or ESP since Part 100 was revised and RG 1.165 was issued in 1997. The impact of the changes as they relate to future plants and operating reactors became apparent when the staff started its review of the ESP applications. In addition, calculated seismic hazard for operating plants in the CEUS region has increased. It should be noted that a complete assessment and review of the operating plants was conducted in response to the Individual Plant Examination for External Events (IPEEE). The NRC staff has determined, based on the evaluations of the IPEEE Program, that seismic designs of operating plants in the CEUS still provide an adequate level of protection. At the same time, the staff also recognizes that the probability of exceeding the SSE at some of the currently operating sites in the CEUS is higher than previously understood [Ref 4].

Some ESP applications adopted an alternative method to that recommended in RG 1.165 [Ref 5]. This alternative is based on the American Society of Civil Engineers Standard 43-05 (ASCE 43-05) [Ref 6]. The alternative is considered “performance based” because it uses a target probability for the maximum acceptable facility damage from an earthquake. RG 1.208 was developed to provide NRC staff guidance on this new method.

In implementing this performance-based approach, the annual frequency of 10^{-5} has been selected as the maximum allowable frequency for the onset of significant inelastic deformation of systems, structures, and components. This target provides a substantial margin to the loads at which core damage and containment failure can occur. The alternative, performance-based, method uses a target frequency that does not change with time as new information on the seismicity of power plant sites is developed.

As a result of this new knowledge, as well as the need of the NRC staff to update several regulations and issue regulatory guidance in support of the review of ESP applications the NRC has conducted seismic and SSI research in four key areas discussed below.

DISCUSSION OF KEY AREAS

Computational Tool

During the late 1980's, Brookhaven National Laboratory (BNL) developed the Computer Analysis for Rapid Evaluation of Structures (CARES) [Refs 7 & 8] program under a NRC sponsored program. CARES was developed to provide the staff with a tool to evaluate the seismic response of relatively simple soil and structural models. BNL has completed an update to CARES by enhancing the analysis capability of the code to perform both deterministic and probabilistic site response and soil-structure interaction (SSI) analyses. The updated CARES code is referred to as probabilistic CARES or P-CARES.

NUREG/CR-6922 [Ref 8] describes the theoretical basis and analysis features for P-CARES, and contains a user's manual. The report also discusses the implementation of: (1) probabilistic algorithms in the code, using various sampling techniques such as Latin Hypercube (LHC) sampling, and traditional Monte-Carlo simulation, to perform probabilistic site response and soil-structure interaction (SSI) analyses; (2) a deterministic free-field response and SSI analyses; and (3) a post processing module, which provides various statistics on the simulation results.

Given that seismic response analyses involve the estimation of the effect of ground motions on structures at a particular site. The uncertainties inherent in ground motion and local site soil properties can be qualitatively considered in P-CARES, which uses a conservative deterministic analysis approach or probabilistic methods (in which uncertainties in earthquake size, location, and time of occurrence are explicitly considered).

The deterministic analysis approach of P-CARES has been validated/benchmarked by its application to a number of problems investigated by the NRC staff: (1) NUREG/CR-6896, "Assessment of Seismic Analysis Methodologies for Deeply Embedded NPP Structures," (2) NUREG-1750, "Assessment of Soil Amplification of Earthquake Ground Motion Using the CARES Code Version 1.2," and (3) NUREG/CR-6584, "Evaluation of the Hualien Quarter Scale Model Seismic Experiment." The probabilistic analysis approach used in P-CARES is based on the seismic probability risk assessment (PRA) method outlined in Appendix B of the American Nuclear Society (ANS) standard, "ANS/ANSI-58.21: External Events in Probabilistic Risk Assessment (PRA) Methodology."

P-CARES includes two SSI models, namely for circular and rectangular foundations. The foundation is assumed to be rigid for both types of foundations. Independent of foundation type, soil is assumed as a two-layered system: a layer to the side of the foundation and a layer beneath the foundation. The SSI model makes use of 6 x 6 stiffness and damping matrices to connect the SSI nodes on the foundation to the free-field. These matrices are generally frequency dependent and are added to the overall structural stiffness and damping matrices. The input motion, i.e., the free-field motion modified by the soil-structure interaction algorithm, is specified as translational and rotational components about each of the global axes. The structure analysis module has more SSI models than the kinematic interaction module; however, if the forcing functions are the generated input motions from the kinematic interaction module, P-CARES will internally choose the same SSI model in the structure analysis module as in the kinematic interaction module for consistency.

Uncertainties inherent in the soil properties and structural properties can potentially cause large variation in soil and structural responses and therefore may have great influence on the inferences obtained during the decision making process. Adequate examination of these uncertainties in the soil and structural system and their impacts on the responses requires a careful layout of the simulation scheme so that the uncertainties can be accounted for with small variation in the statistical estimates and low computational cost. P-CARES includes four sampling schemes for the user to exploit and can be extended straightforwardly if other scheme is in need.

The basic layout of the simulation scheme is illustrated in Figure 1, in which P-CARES core on the right side represents the collection of the deterministic analysis modules and all other components on the left side are for probabilistic simulation. All components in the shaded box contribute to yielding a sample (a realization of the random vector). The simulation controller performs a user-specified number of simulation iterations, each of which involves fetching a sample from the shaded box, invoking the P-CARES core to conduct the free-field and/or SSI analysis, and storing the results in database files. The database files are used in post processing and in transferring free-field responses to the structural analysis module.

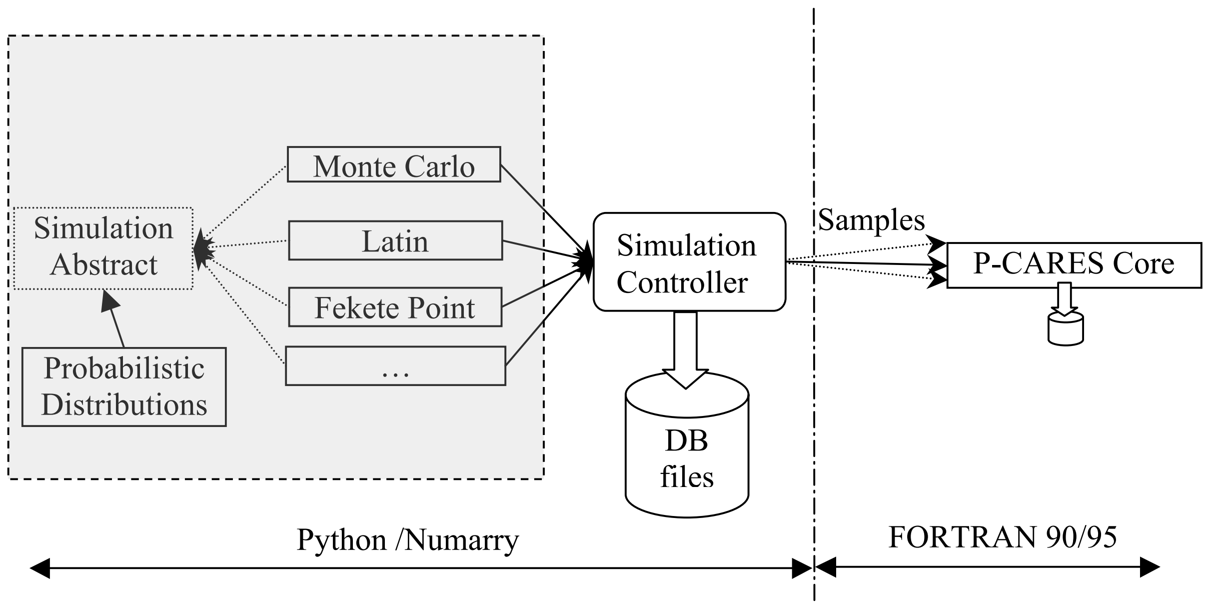

Figure 1 Simulation Concepts in P-CARES

The architecture of P-CARES relies on a fundamental procedure that is shared by all simulation schemes in order to streamline the simulation process and to facilitate future addition of other simulation schemes.

In summary with the development and implementation of the probabilistic and other features, including the addition of a graphical user interface (GUI) to improve the performance of the code, P-CARES provides a coherent approach to effectively perform evaluations of the seismic response of relatively simplified soil and structural models. It also gives the NRC staff the capability to perform a quick check and to carry out parameter variation studies of the SSI models and associated seismic data received from an applicant.

Assessment of Deeply Embedded Structures

Established computer codes used for SSI analysis in the nuclear industry have primarily been developed for current light-water reactors, and applied to coupled SSI models in which the structures are founded at or near the ground surface with shallow embedment. However, several "new generation" NPP designs have proposed deeply embedded or buried (DEB) structural configurations. For two of these new designs submitted to NRC for preliminary review, the entire reactor building and a significant portion of the steam generator building are either partially or completely embedded below the ground surface.

Because current seismic analysis methodologies have been developed for shallow embedded structures, existing regulatory guidance, codes, and standards (e.g., ASCE-4, "Seismic Analyses of Safety-Related

Nuclear Structures") suggest that simple formulations may be used to model the embedment effect when the depth of embedment is less than 30 percent of its foundation equivalent-radius. Therefore, to support the review of preliminary applications for new reactor designs, the NRC has sponsored a research program, under which Brookhaven National Laboratory (BNL) investigates the extent to which procedures acceptable for shallow embedments are also adequate for deeper embedments. The overall objective of this research is to investigate the applicability of existing regulatory guidance, seismic design practice, and SSI computer codes to DEB structures, and recommend any necessary modifications.

A typical safety related structure embedded in a soil profile representative of a typical nuclear power plant site was utilized in the study and the depths of burial (DOB) considered range from 25 – 100% of the height of the structure, see figure 2. NUREG/CR-6896 [Ref 9] includes a discussion of: 1) the description of a simplified analysis and a detailed approach for the SSI analyses of a structure with various DOB (see Figures 3, 4); 2) the comparison of the analysis results for the different DOBs between the two methods (see Figures 5-8); and 3) the performance assessment of the analysis methodologies for SSI analyses of deeply embedded structures. The resulting assessment from this study has indicated that simplified methods may be capable of capturing the seismic response for much more deeply embedded structures than would be normally allowed by the standard practice.

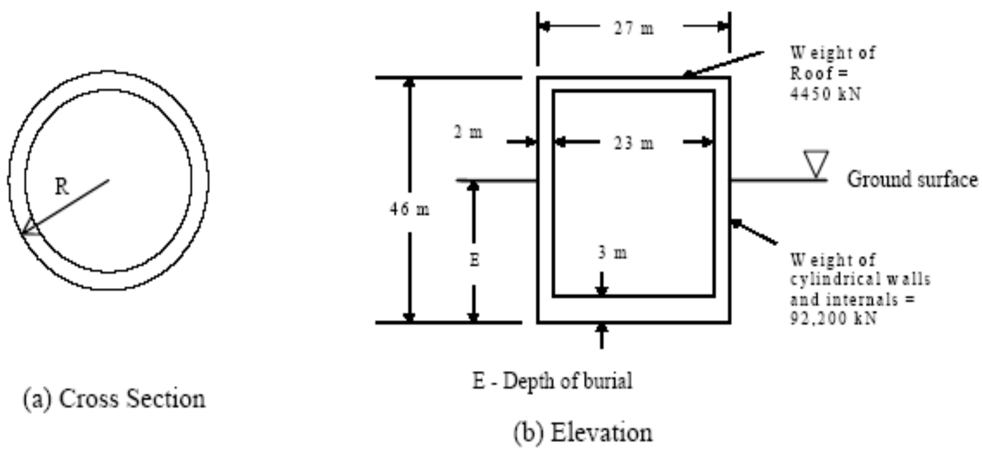

Figure 2. Structure Considered in the Study

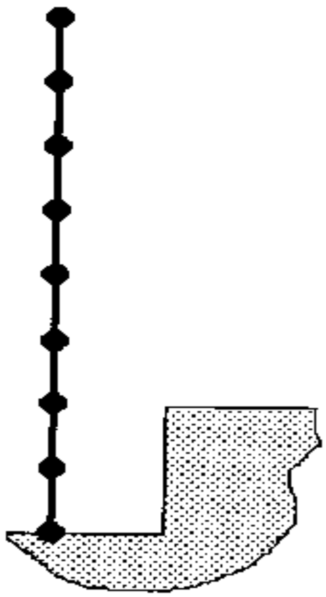

Figure 3. CARES Model

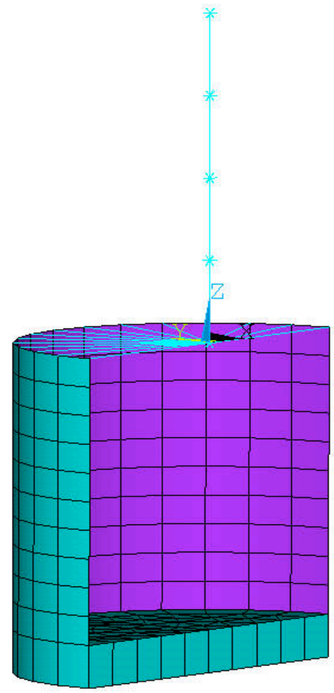

Figure 4. SASSI Model

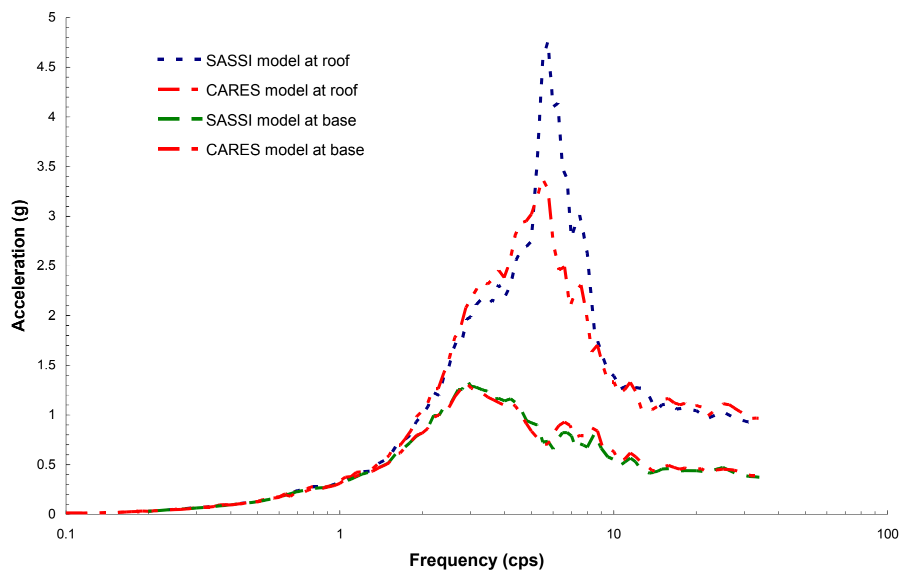

Figure 5. Comparisons of SSI Response Spectra for 25% Embedment (E/R=0.85)

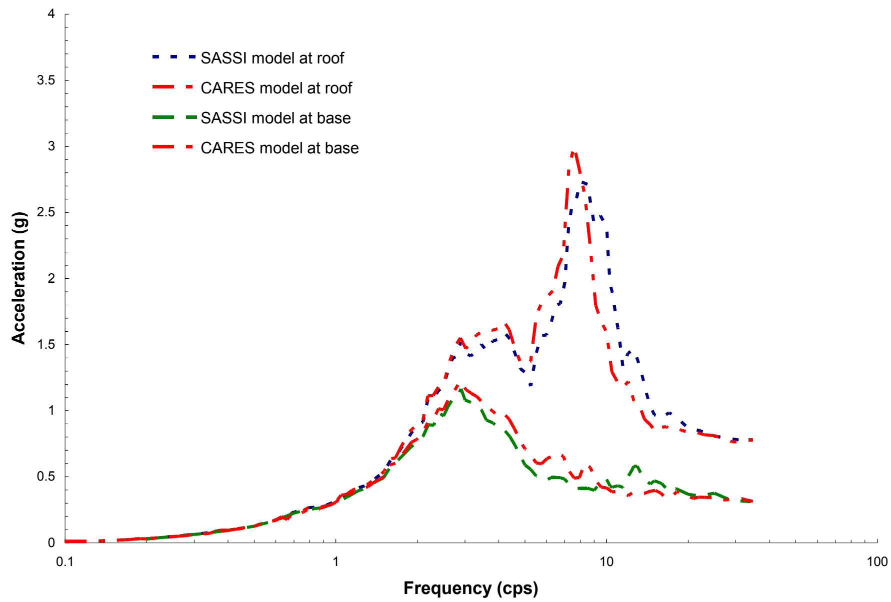

Figure 6. Comparisons of SSI Response Spectra for 50% Embedment (E/R=1.70)

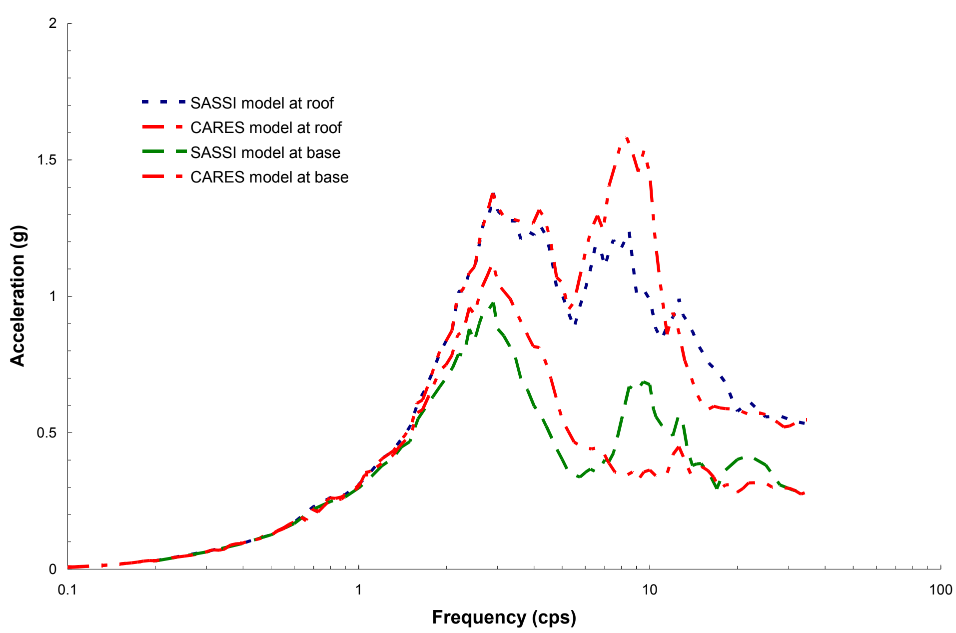

Figure 7. Comparisons of SSI Response Spectra for 75% Embedment (E/R=2.55)

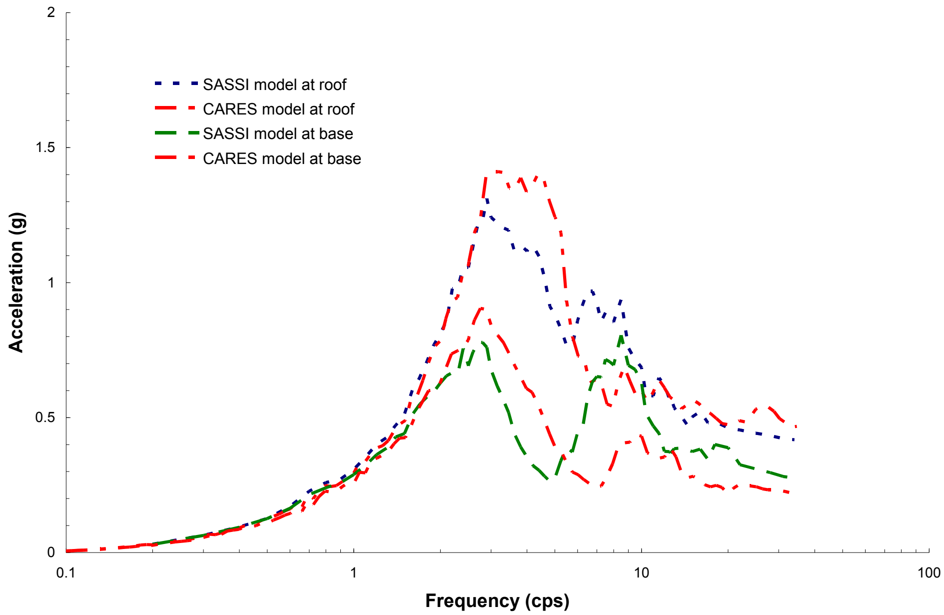

Figure 8. Comparisons of SSI Response Spectra for 100% Embedment (E/R=3.40)

As indicated in Figures 5-8, these comparisons show that in general, the frequency content for the major peak response are consistent between the CARES and SASSI models [Ref 10], and the simplified method appears to produce higher peak response, except for the roof response for E/R=0.85, where SASSI produced much higher response than CARES.

Based on the results of this study, the NRC concluded that existing linear SSI methodologies, including both simplified and detailed approaches can be extended, to varying extents, to DEB structures and produce acceptable SSI response calculations, provided that the SSI response induced by the ground motion is very much within the linear regime or the non-linear effect is not expected to control the SSI response parameters. Furthermore, strong ground motion response data from additional tests or earthquake recordings could prove useful in validating the pertinent modeling assumptions for SSI response analysis of DEB NPP structures.

Performance-Based Method Review Guidance

Use of the methods described in ASCE 43-05 by industry, led to the development of Regulatory Guide 1.208 by NRC staff. Unlike, Regulatory Guide 1.165, Regulatory Guide 1.208 is based directly on the rock-level PSHA uniform hazard response spectra and site response results, coupled with performance- and risk-based approaches for determining the site-specific ground motion response spectrum (GMRS). The annual frequency of exceedance of the ground motions targeted in Regulatory Guide 1.208 is 10^{-5}. The incorporation of a risk-based approach is accomplished through the inclusion of design factors that account for the behavior and performance of frequency sensitive SSCs.

Unlike Regulatory Guide 1.165, Regulatory Guide 1.208 is focused on the site-specific probabilistic motion and does not discuss the development of the safe shutdown earthquake ground motion (SSE). This is because 10 CFR Part 52 ties the definition of the SSE for certified NPP designs to both the site specific and the certified standard design response spectrum (CSDRS). As a result, the development of the SSE is discussed only in the SRP [Ref 1], which also discusses the many related issues such as SSI analyses, the incorporation of incoherency, and others. NRC staff intends to provide new regulatory guidance on SSI analyses that will more comprehensively discuss topics (e. g., SSI, incorporation of incoherency) included in the SRP [Ref 1] once current research is concluded and issues that have arisen in the recent ESP review process are resolved.

Use of Seismic Incoherency in SSI Analyses

Background

As noted in the introduction above, recent advances in seismic hazard models for the CEUS have indicated a possibility of larger seismic motions than was previously predicted. This is particularly true in the high frequency range of seismic motion and is of concern for hard rock sites, where high frequency motion is damped less than in other types of materials. It has been found that at some proposed locations where the NPP is to be founded on hard rock, the calculated site specific ground motion response spectrum (GMRS) is higher than the certified seismic design response spectrum (CSDRS) to which the plant was designed and certified. This seems immediately problematic. However, it is important to note that it is the motions of the soil-structure system that are used to analyze acceptable NPP response and the GMRS is a free-field motion. As a result, significant effort has recently been placed on understanding how high frequency motions are impacted by the NPP structure and systems within the SSI analyses.

Results of SSI analyses indicate that NPP structural systems do not transmit the high frequency ground motion well and much of the high frequency component is removed from the in-structure response spectra used for comparison with certified design limits. This is as expected because the modes that have natural frequencies in the high frequency range typically have low modal contribution to the overall response. In many of the cases where the GMRS exceeds CSDRS in the high frequency range, the results of the SSI analyses indicate a reduction in high frequency motions sufficient to bring the response within tolerable limits. In some cases, the inclusion of additional effects, such as ground motion incoherency, is required. Ground motion coherency is a measure of the degree to which the incoming motions at two points experiencing the same earthquake are in phase at each frequency. Conversely, incoherency is a measure of the degree to which the motions are out of phase.

There are two physical mechanisms that lead to incoherency; wave passage effects and scattering of the incoming waves by the geologic material. The wave passage effects occur due to the time required for the incoming seismic wave front to arrive at different parts of a structure. This effect is a function of the P- and shear wave velocities of the underlying rock and the size of the structure. Scattering of the waves by geologic materials is a function of the fracturing, heterogeneity, stiffness and other properties of the material. Often shear wave velocity is used as a first order parameter in incoherency studies to account for the general geologic properties. Incoherency effects increase with increasing distance and higher frequency content. Incorporating incoherency effects in the SSI analyses would have the effect of reducing motions in the very high frequency range because as motions that are incoherent reach different parts of the foundation the foundation acts to average out the motion and, in effect, acts as a filter.

Development of Incoherency Transfer Function Model

An incoherency transfer function (ITF), has been proposed to the NRC by Electric Power research Institute (EPRI) for use in SSI analyses [Ref 11]. This work has had several iterations and a final ITF has not yet been proposed. The proposed ITFs are based on empirical data from horizontal and vertical arrays that have recorded earthquakes. Most of the data for the initial ITF came from the Strong Motion Array in Taiwan (SMART 1) array and the EPRI Large Scale Seismic Test (LSST) array in Lotung, Taiwan. More recently a significant volume of data has been identified from the Pinyon Flat array in California, and the originally proposed ITF is currently undergoing development. Because the Pinyon Flat array is stationed on hard rock material, it represents key data for this model. This is the case because it is only NPPs sited on hard rock materials that show site-specific GMRS that exceed the CSDRS.

The measure of coherency used in this study is a correlation of the phase angles of the Fourier spectrum of two recorded ground motions. The measure of coherency relates only to phase angle and does not incorporate the amplitude of the wave in any way. This study was based on a plane-wave coherency method, which removes the wave passage effects by aligning two recordings such that the coherency between them over the range of frequencies considered is optimized. This method is the optimal choice for removing wave passage effects from the ITF. This method is in contrast to the unlagged coherency method, which does not align the recordings at all, and the lagged coherency method, which aligns the records differently for each frequency calculation to optimize the coherency at that frequency. Removing wave passage effects was desirable for this study because it is difficult to determine the appropriate seismic wave velocity to use at any particular site.

A recent version of the proposed ITF is shown in Figure 9. Where the measure of coherency is 1, the motions at two points are in phase for the given frequency, this generally occurs in the low frequency range. Where the coherency approaches zero, the phase between two waves are fully random on average. The effects of distance and frequency are apparent in the figure. The reader should note that this is a preliminary figure and will change as studies progress. An updated version will be available through the NRC and EPRI when finalized.

Incorporation in SSI Analyses

Two methods of incorporating the ITF in SSI analyses were investigated by EPRI. First, a direct reduction of the input motion itself was proposed. Secondly, implementation of the ITF at the foundation level of the SSI model was considered. A comparison of the two methods indicated that the results of the SSI were not the same. As a result, methods using a reduction of the input motion are not being pursued further at this time. Instead the ITF is currently being used only within the SSI itself and is implemented as a matrix function at the foundation level [Ref 11].

Currently the investigation has focused on the use of the CLASSI [Ref 13] SSI analysis program. However, recent work has been performed to implement the ITF in the SASSI program as well. In both cases, the results of the analyses have shown a reduction in the horizontal motions in the high frequency range, coupled with an increase in rotation and rocking of the structure, as expected. As a result, the use of and ITF in SSI analyses for the design of NPP will require additional consideration of plant structures, systems and components that may be sensitive to rocking and rotational motions, such as those located on the periphery of the foundation or at the top of the containment structure.

As part of EPRI's research program, it has been determined that the incorporation of the ITF into SSI analyses requires a significant level of understanding of issues beyond those one may ordinarily encounter in the course of SSI modeling. For this reason, user guidelines and a case study will be developed and made available to the SSI modeling community as part of the EPRI program. Both EPRI and the NRC are recommending that each new user of any SSI analysis program that incorporates the ITF produce a validation package based on the EPRI case study prior to their use of the SSI program to develop a NPP application that will be reviewed by the NRC.

Regulatory Guidance

Because the ITF and its implementation are still under development and review, a full discussion of the topic is not included in NRC guidance documents that are being published in spring of 2007. However, a brief discussion of incoherency is included in a revision to Section 3 of the SRP [Ref. 1]. Additionally, as research on this topic progresses at both EPRI and at the NRC, additional documentation will be provided as EPRI reports in the short term and as guidance documents by the NRC staff in the long term.

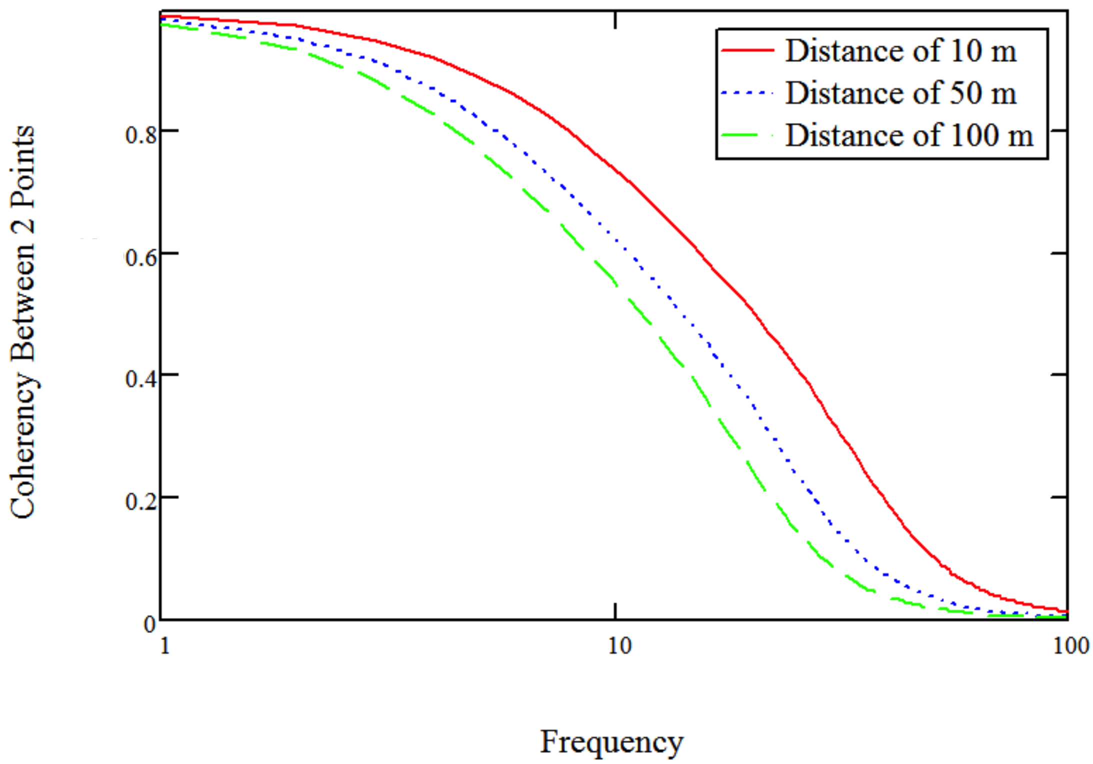

Figure 9. Preliminary horizontal incoherency transfer proposed by EPRI

SUMMARY AND CONCLUSION

Over the last three decades and in the last three years NRC has been involved in seismic and soil-structure interaction (SSI) research. Motivated by advances in industry, recent Early Site Permit applications and the prospect of future Combined Operating License applications the NRC has conducted activities in several key areas. Namely, the development of computational tools, assessment of deep soil sites, and the development of regulatory guidance for performance base reviews, and seismic incoherency in SSI analyses.

With the modification of the CARES code and the development of P-CARES the NRC staff is provided with capabilities to perform deterministic and probabilistic site response and SSI analyses. The probabilistic analysis capability in P-CARES becomes especially important as the nuclear industry is gaining wider acceptance of the probabilistic approach to account for the uncertainties inherent in the natural and built environments.

Based on the NRC assessment of deep and or buried structures (DEB) discussed briefly in this paper, it can be concluded that the linear SSI methodologies, including both simplified and detailed approaches, can be extended to DEB structures and produce acceptable SSI response calculations, provided that the SSI response induced by the ground motion is very much within the linear regime or the non-linear effect is not anticipated to control the SSI response parameters.

It is suggested that additional strong ground motion response data are needed from tests and/or earthquake recordings to validate the pertinent modeling assumptions made for SSI response analysis of DEB NPP structures. Recognizing that it is difficult to obtain such data, additional analytic studies could be performed using the available nonlinear codes to try to determine which parameters of the structure-soil system are controlling SSI responses.

Finally, NRC has worked in the past and will continue to work with US, Japan and researchers from other countries that represent industry, government, and academia to establish necessary seismic and SSI regulations and review guidance.

ACKNOWLEDGEMENT

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DISCLAIMER

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