September 23, 2010

MEMORANDUM TO: Laura A. Dudes, Deputy Director
Division of Engineering
Office of New Reactors

FROM: Kimberly A. Gruss-Hawkins, Chief **/RA/**
Structural Engineering Branch 2
Division of Engineering
Office of New Reactors

SUBJECT: APPROVAL TO PRESENT STAFF PAPER AT AN ORGANIZATION FOR ECONOMIC COOPERATION AND DEVELOPMENT/NUCLEAR ENERGY AGENCY WORKSHOP ON SOIL-STRUCTURE INTERACTION

The enclosed paper was authored by staff to present at the subject workshop on October 6-8, 2010, in Ottawa, Canada. Staff requests approval to submit paper to the workshop organizers by September 24, 2010.

Approved: ____________**/RA/**_________________ Date: September 23, 2010
Laura A. Dudes, Deputy Director
Division of Engineering
Office of New Reactors

Enclosure:
As stated

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U.S. Regulatory Lessons Learned from New Nuclear Power Plant Applications on Evaluating Soil-Structure Interaction[1]

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The objective of this paper is to discuss recent lessons learned from the U.S. Nuclear Regulatory Commission's (NRC's) review of applications for new nuclear power plants from a regulatory and licensing perspective. The paper emphasizes the implementation of the general design criteria in Appendix A, "General Design Criteria for Nuclear Power Plants," and Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants," to Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities,"[2] as it applies to the consideration of the effects of soil-structure interaction (SSI) in evaluating seismic Category I structures, systems, and components (SSCs) for the safe-shutdown earthquake (SSE). The paper discusses applicable U.S. regulations and implementing guidance related to applications for design certifications (DCs) and combined operating licenses (COLs), the establishment of the SSE for the site, and the evaluation of the design of SSCs for an SSE-level earthquake. It also discusses some of the technical issues that the NRC staff has encountered in reviewing the applications and the staff's need for additional information to make appropriate safety determinations.

1. Introduction

SSI analysis is used in nuclear power plant design to evaluate the effects of seismic ground motion on nuclear power plant SSCs important to safety to ensure that they are designed to withstand the effects of natural phenomena (such as earthquakes) without loss of capability to perform their safety functions. The NRC regulations provide the framework for this important design process. General design criteria in Appendix A to 10 CFR Part 50 establish the minimum requirements for the principal design criteria for water-cooled nuclear power plants. They require that nuclear power plants be designed to resist the effects of earthquakes without loss of safety function. The requirements for the establishment of the SSE appear in 10 CFR 100.23, "Geologic and Seismic Siting Criteria."[3] Appendix S to 10 CFR Part 50 provides, in part, requirements for implementing General Design Criterion 2, "Design Bases for Protection against Natural Phenomena," with respect to withstanding the effects of earthquakes for SSCs important to safety. It specifically requires that the seismic analysis for SSE evaluation take SSI effects into account. Staff guidance for reviewing SSI analysis appears in Section 3.7.1, "Seismic Design Parameters," Section 3.7.2, "Seismic System Analysis," and Section 3.7.3, "Seismic Subsystem Analysis," of NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants:

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1 This speech, paper, or journal article was prepared (in part) by an employee(s) of the United States Nuclear Regulatory Commission. It presents information that does not currently represent an agreed-upon staff position. NRC has neither approved nor disapproved its technical content.

2 *U.S. Code of Federal Regulations*, Title 10, *Energy*, Part 50, "Domestic Licensing of Production and Utilization Facilities."

3 *U.S. Code of Federal Regulations*, Title 10, *Energy*, Part 100, "Reactor Site Criteria."

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LWR Edition"[4] (hereafter referred to as the SRP), as supplemented by the applicable regulatory guides (RGs) and interim staff guidance (ISG).

While not new to the design of nuclear power plants, SSI analysis has evolved in the recent decade from employing lumped-mass beam models to using full three-dimensional finite element models with a high degree of fidelity. Further, the use of updated seismic source and ground motion models by applicants for new reactors has led to higher seismic hazard estimates, particularly in the high frequency (HF) range, in the Central and Eastern United States. The evaluation of this change in seismic hazard estimate in the HF range generally requires a more refined seismic SSI model. As a result, applicants for DCs and COLs are developing detailed finite element models to assess the effects of this HF ground motion on the design of SSCs. SSI computer programs such as SASSI and CLASSI have incorporated seismic wave coherency functions that account for spatial variation in seismic ground motion input. Regulatory requirements, review guidance, and examples of lessons learned are provided below.

2. Regulatory requirements

Under General Design Criterion 2, each applicant for a construction permit, operating license, DC, COL, or design approval is required to design nuclear power plant SSCs that are important to safety to withstand the effects of natural phenomena, such as earthquakes, without loss of capability to perform their safety functions. The design bases for these SSCs shall reflect appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin to account for uncertainties.

Under 10 CFR 100.23, COL applicants are required to investigate the geological, seismological, and engineering characteristics of a site and its environs to obtain sufficient information to support the evaluations performed to estimate the SSE.

Appendix S to 10 CFR Part 50 describes the requirements for the development of an acceptable SSE, including that the SSE must be a smoothed free-field ground motion response spectrum (GMRS) at the free ground surface. It also stipulates that the horizontal component of the SSE ground motion at the foundation level must be an appropriate response spectrum with a peak ground acceleration (PGA) of at least 0.1g. Further, the nuclear power plant must be designed so that certain SSCs remain functional in the event of an SSE, considering applicable concurrent loads. The evaluation must take into account SSI effects and the expected duration of vibratory motion.

3. Review guidance

SRP Sections 3.7.1 and 3.7.2 provide NRC review guidance pertaining to the development of SSI models, including input parameters, structural modeling assumptions, structural damping, secondary systems, and model fidelity. ISG-1, "Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications,"[5] and ISG-17, "Ensuring Hazard Consistent Seismic Input for

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4 NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," U.S. Nuclear Regulatory Commission, Washington, DC.

5 ISG-1, "Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications," U.S. Nuclear Regulatory Commission, Washington, DC.

Response and Soil Structure Interaction Analyses,"[6] complement this guidance. SRP Section 3.7.1 provides guidance for the review of design ground motion. For a DC application, the staff reviews the postulated seismic design response spectra and their input or control location. For a COL application referencing a certified design, the staff reviews the applicant's demonstration that the site-specific ground motion is enveloped by the standard plant[7] design response spectra. SRP Section 3.7.2 relates to the review of seismic analysis models and the incorporation of SSI effects. ISG-1 and ISG-17 relate to the review of HF effects on SSCs and to ensuring a consistent approach for developing foundation input response spectra (FIRS).

4. Lessons Learned

The staff is currently reviewing several DC and COL applications and has encountered common issues that have posed challenges to the reviews, discussed briefly below.

4.1 Defining the safe-shutdown earthquake for a site

A COL applicant referencing a certified design must establish a site-specific SSE to determine if the standard design may be used for the site. ISG-17 provides detailed guidance for this purpose. For the design of nuclear power plants, the SSE is defined as the vibratory ground motion for which certain SSCs are designed to remain functional, pursuant to Appendix S to 10 CFR Part 50. The SSE for the site is characterized by both horizontal and vertical free-field GMRS at the free ground surface. For a COL applicant, the SSE may be defined corresponding to the site-specific GMRS provided that the horizontal component of the SSE ground motion in the free field meets the 0.1g requirement at the foundation level of the applicable structures. RG 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion,"[8] provides guidance for the development of the site-specific earthquake ground motion. The standard plant design only establishes the design-basis loading; that is, from a structural point of view it establishes the pressure, temperature, seismic, tornado, hurricane, and other design-basis loads. Most standard plant designers have based the certified seismic design response spectra[9] (CSDRS) on those given in RG 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants,"[10] anchored at 0.3g. It is incumbent on the COL applicant to demonstrate that these design-basis loads are not exceeded for the specific site. Because COL sites have had amplified HF ground motion and site-specific seismic design parameters not bounded by the DC, COL applicants are performing site-specific confirmatory SSI evaluations. Few standard plant designers have modified their proposed CSDRS to account for the amplified HF motion. COL applicants are also required to perform site-specific SSI analysis for site-specific SSCs (i.e., those not designed at the DC stage, such as the ultimate heat sink structure) that are important to safety. The design of SSCs considers two levels of design ground motion: the

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[6] ISG-17, "Ensuring Hazard Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses," U.S. Nuclear Regulatory Commission, Washington, DC.

[7] *Standard plant (or design)* is a design which is sufficiently detailed and complete to support certification or approval and which is usable for a multiple number of sites without reopening or repeating the design certification review.

[8] RG 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion," U.S. Nuclear Regulatory Commission, Washington, DC.

[9] *Certified Seismic Design Response Spectra* (CSDRS) is the site-independent seismic design response spectra that have been approved under Subpart B, 10 CFR Part 52, as the seismic design response spectra for an approved certified standard design nuclear power plant.

[10] RG 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Washington, DC.

operating-basis earthquake (OBE) and the SSE. The OBE is an earthquake that could be expected to affect the site of a nuclear reactor, but for which the plant's SSCs remain functional without undue risk to public health and safety. If the OBE is set at one-third or less of the SSE, then further analysis or design is not explicitly required. This provides conservatism in that the design performed using the SSE will be adequate to meet OBE design criteria. If the vibratory ground motion exceeds the OBE level, a plant shutdown is required.

4.2 Developing the foundation input response spectra

The COL applicant must compare the site-specific GMRS/FIRS to the standard plant design CSDRS at the appropriate elevation. These FIRS are developed as free-field outcrop spectra. A consistent site-specific analysis should be used to develop the GMRS and FIRS in accordance with ISG-17. Deterministic SSI calculations typically use FIRS as free-field input motion to the site-response calculation. NRC regulations (Appendix S to 10 CFR Part 50) require that FIRS horizontal motion in the free field, at the foundation elevation of seismic Category I structures, be an appropriate response spectrum with PGA of at least 0.1g. The response spectrum associated with this minimum PGA should be a smooth broad-band response spectrum (i.e., that given in RG 1.60, or another appropriately shaped spectrum if justified) for comparison purposes.

The COL applicant must also compare the site-specific soil/rock properties (shear wave velocity profiles) to those assumed for the standard plant SSI analysis. If the COL applicant's site-specific GMRS exceed the standard design CSDRS, or the site soil/rock properties are not consistent with those for the standard plant, the COL applicant must perform a site-specific analysis to demonstrate that SSCs will remain functional.

The engineering properties of soil are strain dependent and can be highly nonlinear. Therefore, it is essential to ensure that the characterization of soil layers and their associated properties used in the GMRS analysis are also those used for development of the site-specific FIRS (i.e., consistent response spectra). ISG-17 provides relevant NRC guidance.

4.3 Soil Modeling

The factors to consider in modeling SSI are the extent of embedment, the layering of rock/soil strata, the soil element size capable of transmitting the frequencies of interest, and the boundary of the SSI model. Associated uncertainties are the random nature of the soil and rock configuration and material characteristics, soil constitutive modeling, nonlinear soil behavior, lack of uniformity in the soil profile, effects of basemat flexibility, the effect of pore water on structural responses, and effects of partial separation or loss of contact between the soil and the structure. To address these uncertainties, sensitivity studies should be conducted to identify important parameters for a given site condition. If HF ground motion response is to be evaluated, then the adequacy of the soil-structure model should be verified for 50 hertz (Hz) using ISG-1. The properties used in SSI analysis should be consistent with the soil strains developed in the free-field site response analysis. The behavior of soil, while recognized to be nonlinear, can be approximated with linear analysis techniques. The characterization of soil properties used in SSI analysis is further described in SRP Section 3.7.2.

Three soil/rock profiles should be considered in the site-specific SSI analysis: a best estimate, a lower bound, and an upper bound profile. The properties of each soil layer are defined in terms of strain-dependent modulus degradation and strain-dependent hysteretic damping relationships. These properties are typically developed from laboratory tests such as resonant column torsional shear tests.

4.4 Structural model

In general, three-dimensional models (lumped mass or finite element models or both) should be used for seismic analysis. Improvements in computational efficiency have resulted in the increased use of finite element models that are capable of resolving high levels of structural detail. Further, these models can directly account for dynamic amplification caused by out-of-plane response of floors and walls. The structural model should be sufficiently detailed to capture the significant structural response modes. If analysis of HF ground motion is addressed, the SSI and structural models should be adequately refined to sufficiently capture the HF content of the horizontal and vertical GMRS/FIRS in the structural response. The frequency range of HF to be transmitted should cover a model refinement frequency of at least 50 Hz. ISG-1 provides further guidance on HF evaluation.

Major equipment masses (e.g., reactor coolant system) should be represented in the structural model, and minor equipment, piping, and raceways can be represented by a 50-pound-per-square-foot uniform dead load.

A complete SSI model should properly account for all effects related to kinematic and inertial interaction for surface or embedded structures. To account for uncertainties in SSI analysis, sensitivity studies should be performed to identify important parameters and to assist in judging the adequacy of the final results. Further guidance for accounting for SSI modeling uncertainties is described in SRP Section 3.7.2.

The SSI model should consider water tanks internal to the reactor building. SRP Section 3.7.3, “Seismic Subsystem Analysis,” provides guidance for considering the convective (sloshing) and impulsive (rigid) response of the tank.

4.5 Structural damping

Damping in dynamic analyses accounts for energy dissipation from friction in connections, slight concrete cracking, and localized inelastic material behavior caused by seismic demands. This energy dissipation is represented by viscous damping where the damping force is proportional to velocity. The selection of damping is made at two steps: first, for defining the value of structural damping in the seismic analysis model, and second, for defining damping used for the generation of the in-structure response spectra. RG 1.61, “Damping Values for Seismic Design of Nuclear Power Plants,”[11] provides guidance on damping values used in the analysis. Use of OBE-level damping for the generation of the in-structure response spectra is conservative. However, the applicant must justify the use of other damping levels in excess of OBE-level damping values for generation of the in-structure response spectra.

11 RG 1.61, “Damping Values for Seismic Design of Nuclear Power Plants,” U.S. Nuclear Regulatory Commission, Washington, DC.

4.6 Structure-soil-structure interaction

The effects of adjacent structures on the seismic response and the dynamic soil pressure caused by structure-soil-structure interaction (SSSI) should be considered. Of significance is the potential for the amplification of seismic demands on the lighter structure because of the response of the heavier structure. Staff review of several DC and COL applications has resulted in additional work in analyzing the effects of lateral pressures caused by SSSI on buried structures (tunnels, piping) and adjacent structures.

4.7 Backfill considerations

The SSI analysis should consider backfill beneath and adjacent to seismic Category I structures. The selection of lean concrete or granular backfill material beneath a seismic Category I structure can affect the dynamic response of a reactor building structure or any adjacent structures. Further, the selection of backfill may also affect the response of the adjacent structures. Backfill properties used in the analysis should be verified once the backfill is placed. The properties used for analysis should be consistent with the expected mean strain levels along with the expected lower and upper bound values.

4.8 Soil separation and dynamic soil pressure

SSE-level demands on a nuclear island or other seismic Category I structure may cause uplift or soil separation along the sides of the embedded foundation. The dynamic soil pressure for an embedded wall design should consider the inertial effect of massive buildings and should be evaluated based on the results of an SSI or SSSI analysis.

COL applicants should ensure that the DC design bases for dynamic soil pressures are bounding and consistent with the specific site. The sliding stability of the nuclear island should be assessed using the site-specific friction coefficient, since this value is highly dependent on the site characteristics.

4.9 Incoherency effects

Many DC and COL applicants are developing SSI models that incorporate the effects of seismic ground motion incoherency functions. The incoherency of seismic waves has been recognized for several decades as having an effect on structures with large dimensions. The incoherency of seismic waves generally results in a reduction of structural translational responses when compared with coherent seismic motion, especially in the higher frequency ranges (e.g., frequencies greater than 10 Hz). For the structures of large dimensions typical of nuclear power plants designs, these translational modes can be reduced because of wave scattering, but torsion and rocking modes can be induced that can result in increased response at locations remote from their center of mass.

ISG-1 specifies an acceptable approach to consider the effects of incoherency on the nuclear island foundation when there is HF seismic ground motion. The staff accepts the use of the proposed horizontal and vertical coherency functions as discussed in ISG-1. As mentioned in Section 3.4 of this paper, the SSI model refinement should be reasonably accurate up to 50 Hz.

5. Conclusion

The NRC regulations provide the framework for the safety review of nuclear power plant designs to ensure that they will result in a plant that can withstand the effects of natural phenomena (such as earthquakes) without loss of capability to perform safety functions. The staff has access to comprehensive guidance in the form of publically available RGs and ISGs for use in reviewing applications and making safety determinations. In some special cases, such as those mentioned above, the staff has observed that additional information is needed to make the safety determination. While SRP guidance constitutes an acceptable approach, applicants can use alternative approaches if they provide adequate justification and information for the staff to perform its safety review. The staff will review these special situations on a case-by-case basis.