Interim Staff Guidance
on Ensuring Hazard-Consistent Seismic Input
for Site Response and Soil Structure Interaction Analyses
DC/COL-ISG-017

1.0 Purpose

This interim staff guidance (ISG) supplements the guidance provided to the staff in Sections 2.5 and 3.7 of NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," issued March 2007 (hereafter referred to as the Standard Review Plan (SRP)) (Ref. 1) and ISG-01, "Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications," issued May 19, 2008 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML081400293) (Ref. 2). Section 5.0 of this ISG provides the staff position on the following issues: (1) comparing Certified Seismic Design Response Spectra (CSDRS) to the site-specific seismic demand for various foundation conditions analyzed in the certified design, (2) deriving foundation input response spectra (FIRS) consistent with the site response used in site-specific ground motion response spectrum development employing either one of two options, (3) satisfying minimum seismic input requirements, and (4) documenting findings. This ISG is applicable to the review of seismic design information submitted to support combined license (COL) applications.

2.0 Basic Terms and Concepts

The detailed technical basis used to develop this ISG appears in the Nuclear Energy Institute[1] (NEI) white paper entitled, "Consistent Site-Response/Soil-Structure Interaction Analysis and Evaluation," dated June 12, 2009 (ADAMS Accession No. ML091680715) (Ref. 3), and Brookhaven National Laboratory (BNL) Report N6112-051208, Revision 1, "Consistent Site Response-SSI Calculations," dated July 15, 2009 (ADAMS Accession No. ML091980384) (Ref. 4). These references contain a detailed discussion of issues and stepwise procedures to implement the technical positions outlined in this ISG. This ISG is to be used in conjunction with these two documents.

This section defines key terms and concepts that are used in this ISG. Some of the definitions presented here are repeated from ISG-01, with some additional discussion to provide the context for this ISG.

[1] The NEI New Reactor Seismic Issues Resolution Program undertook several studies producing industry white papers. The guidelines developed in ISG-01, the NEI white paper, and the development of the criteria associated with this ISG result from the coordination of the industry initiative (Ref. 3), U.S. Nuclear Regulatory Commission (NRC) studies (Ref. 4), and other stakeholder inputs through interactions in public meetings. In particular, the meeting of September 25–26, 2008, was instrumental in establishing a framework of common understanding (see meeting summary, ADAMS Accession No. ML082950476 (Ref. 5)).

CSDRS - Are site-independent seismic design response spectra that have been approved under Subpart B, “Standard Design Certifications,” of Title 10 of the *Code of Federal Regulations*, Part 52 (10 CFR Part 52), “Licenses, Certifications, and Approvals for Nuclear Power Plants” (Ref. 6), as the seismic design response spectra for a nuclear power plant (NPP) using an approved certified standard design.

Ground Motion Response Spectra (GMRS) - Are site-specific and are characterized by horizontal and vertical response spectra determined as free-field motions on the ground surface or as free-field outcrop motions on the uppermost in situ competent material using performance-based procedures in accordance with Regulatory Guide (RG) 1.208, “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion” (Ref. 7).

Effect of Overburden in the Soil Profile Properties - When a site has weak surficial layers of soil that are to be removed and replaced by structural backfill, the outcrop elevation for the GMRS analysis of the site soil profile may be the elevation above which the weak surficial layers are to be removed. The soil above the outcrop elevation is not incorporated into the site column response calculation. However, the calculation needs to capture the effect of the weight of the soil overburden in producing confinement that affects the soil properties and includes the effects of the soil column frequency of the overburden soil. Therefore, all computation of overburden pressures needs to include the weight of the soil column above the outcrop elevation to ensure that the computation of nonlinear effects in the strain iteration process is done consistently to match the final configuration of the site profile.

FIRS - The performance-based site-specific seismic ground motion spectra at the foundation levels in the free field are referred to as the FIRS and are derived as free-field outcrop spectra. The FIRS is the starting point for conducting a soil-structure interaction (SSI) analysis and making a one-to-one comparison of the seismic design capacity of the standard design and the site-specific seismic demand for a site. The FIRS for the vertical direction is obtained with the vertical to horizontal (V/H) ratios appropriate for the site.

Full Column Outcrop - Ground motion is an outcrop motion that includes the full effect of the soil above (e.g., outcrop ground motion from a one-dimensional iterative dynamic soil column analysis program like SHAKE). The full column outcrop includes the effects of down-coming waves from soils above the elevation of the outcrop.

Geologic Outcrop - Is the surficial expression of a layer of subsurface material that occurs at a site either close to the foundation location or some distance away from it. The engineering significance of the term “geological outcrop” is “that there is no soil overburden on top of the outcrop where there should be none.” The free-field ground motion corresponds to a free surface condition, such that there is no soil above (no down-coming waves), but the confining pressure of any soil above is considered for evaluating the nonlinear effects included in computation of G/Gmax and damping versus strain.

Outcrop Elevation - An outcrop assumption implies that the outcrop surface is a free surface at which the boundary condition for seismic waves is no shear stress, leading to a complete reflection of the incident wave. However, in reality, there may be layers of soil above the assumed outcrop elevation. In these situations, the GMRS or FIRS is computed at depth in a soil profile that includes the effect of the soil layers above on the properties of soil layers below.

Performance-Based Surface Response Spectra (PBSRS) - Are the performance-based free surface response spectra generated using the soil column corresponding to the building for which the performance-based FIRS are also generated. The properties of the soil column usually consist of 60 or more randomized sets of properties similar to those used in the probabilistic seismic hazard analysis (PSHA) process. The resulting spectrum, described above, is the PBSRS for the horizontal direction. The PBSRS for the vertical direction is obtained with the appropriate V/H ratios used to develop the GMRS. PBSRS are used to verify and ensure that the soil columns to be used in a deterministic SSI analysis produce surface response spectra that envelope the PBSRS. PBSRS are associated with subsurface conditions localized to a specific building. GMRS are those derived from the global understanding of the site soil layers above the rock condition as determine from the site exploration activities, and therefore, are unique to a particular site.

Site Response Analysis - A PSHA is carried out to obtain the uniform hazard spectra (UHS) at the mean annual probability of exceedance (MAPE) of 10^{-4} and 10^{-5} at the base of the site soil profile. Since the site-specific soil column amplifies and modifies the input ground motion from the base, and because the engineering properties of soil are variable, uncertainties associated with the properties of each layer of soil are incorporated in the soil profile to perform the site amplification analysis to obtain the UHS at the free surface in the free field. To consider variation and uncertainties in dynamic soil properties, they are randomized (using a Monte Carlo type of sampling from the properties of each layer, such as shear moduli and damping values) and a suite of typically 60 randomized soil profiles are generated for soil amplification analysis. Soil amplification analysis is performed, and the response motion at the free surface is obtained as the mean response motion at the two levels of the input motion 10^{-4} and 10^{-5} MAPE. A frequency-dependent design factor is computed using the uniform hazard soil surface motions. The design factor is applied to the soil response motion at the MAPE of 10^{-4}, and the design response spectrum is developed. Once the horizontal design response spectrum is obtained, the vertical design response spectrum is developed using the appropriate V/H ratios for the site. RG 1.208 and NUREG/CR-6728, "Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk- Consistent Ground Motion Spectra Guidelines," issued October 2001 (Ref. 8), describe the development of performance-based motion in detail.

Site Soil Profile - Consists of all the soil layers between the ground surface and the elevation below which there is a rock/soil stratum with a shear wave velocity of about 9,200 feet per second (ft/s).

Soil Column - Is a representation of the site soil layers used in the site response analysis that is developed with the actual soil layer properties determined from the site exploration program. The best estimate soil property should be obtained from the interpolation of the median strain-compatible soil properties corresponding to the soil column analyses using 10^{-4} and 10^{-5} MAPEs rock motions. The upper bound and lower bound soil column properties are obtained from the variation of the strain-compatible soil properties from the median profile. Typically, one standard deviation is used to define the upper and lower bound values

SSI Analysis - A process that is driven by a set of deterministic criteria described in SRP Sections 3.7.1 and 3.7.2. SSI analysis is to be performed using three soil columns. These soil columns are based on the mean plus or minus one standard deviation of the strain-compatible properties of each layer of the randomized soil profiles used for the site response analysis. The mean (or best estimate), mean plus one standard deviation (or upper bound), and mean minus one standard deviation (or lower bound) soil profiles represent the range of variation of the dynamic soil properties for each layer in the soil column, subject to limits on the soil shear modulus as discussed in position 5.2.2. Thus, the soil columns used in the SSI analysis are no longer in strict compatibility with the input motion as a result of using the statistics of each layer as its representative and the averaging of the motions derived from each soil profile in developing the input motion.

Truncated Soil Column Response (TSCR) - Is, in effect, the free surface outcrop motion. In order to obtain the TSCR, a SHAKE analysis (a commercial program for one-dimensional wave propagation analysis) for the full soil column with no truncation is carried out to develop a set of strain-compatible soil velocity and damping profiles. Once the strain compatible soil profiles are obtained, the soil layers corresponding to the embedment depth of the structure are removed, and a second round of soil column analysis is carried out with the truncated soil columns and no further iteration on soil properties. The resulting response motions at the truncated surface are obtained as TSCR. This is discussed in Ref. 3.

UHS - The site-specific UHS are developed for elevations that correspond to site-specific soil/rock stratum where the low strain shear wave velocity is about 9,200 ft/s.

3.0 Background and Discussion of Issues

A probabilistic approach is used to define the site-specific seismic hazard, which is modified by a performance-based methodology to establish the site-specific GMRS. The following key steps are involved in this process:

(1) Rock UHS is calculated at the rock horizon under the geologic outcrop condition.

(2) The site surface UHS is calculated, incorporating soil response at the free surface that accounts for the dynamic characteristics of the site soil profiles, which include the use of the randomized soil properties of each layer from 60 or more sets of soil column profiles.

(3) The site surface UHS are scaled by applying a set of frequency-dependent design factors to obtain performance-based response spectra, the GMRS.

The resulting GMRS, a performance-based ground motion response spectrum, is then used in the deterministic SSI analysis. Currently available SSI computer codes are capable of internally transferring the surface motion to the appropriate foundation level for input to the SSI model. Since this computation is conducted in deterministic space, procedures are needed to ensure that the foundation-level motion obtained from the SSI computer code, when propagated to the surface, will be consistent with the original surface motion for both the horizontal and vertical directions. Therefore, a deterministic SSI computation should start with a foundation-level input motion (i.e., FIRS).

Another issue is related to the consistency between the results of deterministic SSI analyses based on three site column profiles versus results from a probabilistic approach that uses 60 site column profiles.

Section 5.1 of the ISG provides guidance on comparing CSDRS with FIRS under three different situations. This step helps determine whether or not SSI analyses are needed for certain site-specific seismic demands.

Section 5.2 of the ISG provides guidance on acceptable methods that would allow the retention of compatibility between the computed performance-based seismic motions and the FIRS used in the SSI analysis, when the comparisons carried out in Section 5.1 are not conclusive for other reasons.

In order to determine whether or not the seismic design response spectrum of a certified standard reactor design envelops the seismic demand spectrum at a specific site, it is necessary to compare the site-specific GMRS or the site FIRS and the CSDRS at the same reference elevation. Since the CSDRS is site independent, the seismic motion can be prescribed at the free surface or the foundation elevation of a structure incorporated in the standard design. Therefore, any comparison of the CSDRS must be made at the corresponding elevation at a specific site using soil properties consistent with the site GMRS analysis. As the engineering properties of soil are strain-dependent and can be highly nonlinear, 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 the site-specific FIRS determination at various foundation elevations.

Section 5.3 of the ISG provides a procedure for performing the necessary checks to meet the minimum seismic input requirement at the foundation. As described in SRP Section 3.7.1, and required by Section IV(a)(1)(i) of Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities" (Ref. 9), the horizontal component of the input motion should not be less than the suitable broad-band spectrum scaled to 0.1g. The acceptance criteria in SRP Section 3.7.1 specify the following:

> The response spectrum associated with this minimum peak ground acceleration (PGA) should be a smooth broad-band response spectrum (e.g., RG 1.60 [Ref. 10] or other appropriately shaped spectrum if justified) considered as an outcrop response spectrum at the free-field foundation level. This response spectrum anchored at 0.1g will be referred in this SRP section as the minimum required response spectrum.

Section 5.4 of the ISG describes the information and results necessary for the NRC staff to conduct a review and prepare pertinent safety evaluation reports.

4.0 Applicability

This ISG will be implemented on the day following its issuance. It will remain in effect until it has been superseded, withdrawn, or incorporated into a revision of the SRP and RG 1.206, "Combined License Applications for Nuclear Power Plants (LWR Edition)" (Ref. 11).

5.0 Proposed ISG and Technical Positions

5.1 Position on Comparison of CSDRS with the Site-Specific Seismic Demand

The procedures described in Section 3.1 of the NEI white paper (Ref. 3) are acceptable for comparing FIRS with CSDRS to determine the applicability of the certified design. Although Appendix D to SRP Section 3.7.1 shows the steps involved in the review of COL applications with or without referencing a certified design, the SRP (Ref. 1) does not provide details on the use of hazard-consistent soil properties. The NEI white paper describes three different situations, discussed below: surface structures, embedded structures analyzed as surface structures in the design control document (DCD), and embedded structures analyzed as embedded structures.

5.1.1 Surface-Founded Structures with No Embedment

When the certified design is a surface-founded structure and the SSI analysis for the design has been approved with an SSI model and no embedment, the procedures described in Section 3.1.1 of the NEI white paper (Ref. 3) are acceptable for this comparison. FIRS are the same as PBSRS. The horizontal and vertical FIRS are compared with the corresponding CSDRS, and the decision on the need for a site-specific SSI analysis is made on the basis of the comparison.

5.1.2 Embedded Structures Analyzed as Surface Structures in the Certified Design

When the NRC approves the seismic design and analyses of some structures in certified design as surface structures with no embedment considered in the SSI analysis, based on the use of numerous soil profiles that cover a wide range of site conditions, the procedures described in Section 3.1.2 of the NEI white paper (Ref. 3) are acceptable for this comparison. The FIRS should be computed as the TSCR spectra and compared with the CSDRS. For computation of FIRS as the TSCR, the truncated soil column should include the effect of soil layers above the foundation depth on the nonlinear soil properties of the soil layers below, in terms of both the confining pressure and the soil column frequency of the soil layers above the truncated depth. One direct approach to include these effects in the analysis is to perform the soil column analysis for the full soil column with no truncation and develop the set of strain-compatible soil velocity and damping profiles. Once the strain-compatible soil profiles are obtained, the soil layers corresponding to the embedment depth of the structure are removed and the second round of soil column analysis is performed with the truncated soil columns with no further iteration on soil properties. The FIRS in the horizontal and vertical directions are compared with the corresponding CSDRS in the respective directions, and the decision on the need for a site-specific SSI analysis is made.

5.1.3 Embedded Structures Analyzed as Embedded Structures in the Certified Design

The procedure described in Section 3.1.3 of the NEI white paper (Ref. 3) is acceptable with the following considerations. The procedure in Section 3.1.3 of Ref. 3 states that the envelope of the CSDRS-based FIRS for all the generic soil properties is obtained and used for the comparison. This is acceptable if the design loads and the in-structure response spectra were based on the envelope of all the generic soil profiles in the DCD.

5.2 Position on Site-Consistent Seismic Input and Soil Profiles Properties for the SSI Analysis

When a site-specific SSI analysis is conducted, two approaches are acceptable to obtain the site-consistent seismic input for the SSI analysis. Either one of the two approaches can be used for this purpose. However, before conducting a detailed SSI analysis, it is essential to demonstrate that the PBSRS are enveloped by the FIRS convolved up to the surface using the three soil properties for the SSI model—upper bound, best estimate, and lower bound. The basic steps of these two options are described below. Whichever option is chosen, the detailed steps in the selected approach must be followed, as described in the NEI white paper (Ref. 3) for the first approach and the BNL report (Ref. 4) for the second.

5.2.1 Option One

This approach begins with the determination of the rock UHS. The soil profile amplification analysis is conducted to obtain the resulting mean UHS at the desired elevation for 10^{-4} and 10^{-5} MAPE. From the 10^{-4} and 10^{-5} MAPE hazard curves, a frequency-dependent set of design factors is used to obtain a fully performance-based response spectrum. The procedures described in Sections 2, 3.1, and 3.2 of the NEI white paper (Ref. 3) are acceptable to develop input motions and soil profiles for the site-specific SSI analysis.

The NEI white paper covers different outcrop surface conditions: for example, the full soil column, or where soil from the upper layers has been removed and a truncated soil column is used in the site response analysis. Both surface-founded and embedded foundation conditions are addressed.

A very critical element of this procedure is a verification (see steps 3, 4, and 5 in Section 3.2.3 of the NEI white paper) that input seismic motions used for the SSI analysis model for the three deterministic soil conditions adequately bound the PBSRS in both the horizontal and vertical directions. This verification is a critical part of the staff review.

5.2.2 Option Two

In the second approach, the starting point is the same UHS elevation. Next, the fully performance-based FIRS is obtained as a geological outcrop motion. During this process of obtaining the fully performance-based FIRS, it is necessary for subsequent SSI analysis to obtain the deterministic soil column properties that are consistent with the FIRS, as described above. From the set of soil profiles used in the soil amplification analysis corresponding to the 10^{-4} MAPE analysis to develop the FIRS, a companion set of strain-compatible soil shear wave velocity and damping properties are obtained. From this set, the best estimate and one standard deviation of the soil velocity and damping for each soil layer are computed. The best estimate, the lower bound, and the upper bound soil properties for SSI analysis are obtained from the mean properties plus or minus one standard deviation, maintaining the minimum variation of $1.5xG_{best}$ and $G_{best}/1.5$ to define the range as required in SRP Section 3.7.2, where the term “best” denotes the best estimate properties.

In this option, the free surface is assumed to be a geologic outcrop such that there is no material on top of the free surface. Procedures described in Section 5.0 and 6.0 of the BNL report (Ref. 4) are acceptable to develop input motions and soil profiles for the site-specific SSI analysis.

Like the NEI white paper, the BNL report covers different situations related to surface or embedded foundations.

5.2.3 Specification of Seismic Input Motion for Site-Specific SSI Analysis When Needed

All SSI seismic analyses should be conducted using the FIRS as the input at the foundation elevation of the SSI model. For SSI methods that do not permit outcrop input, the FIRS need to be transferred to the in-column motions using the SSI profiles with no further iterations on soil properties. The soil profiles and the associated properties to be used for the SSI analysis should be derived from the process as described in Positions 5.2.1 or 5.2.2 above. The outcrop definition (geologic outcrop versus full-column outcrop) and the method for its transfer to the in-column motions for the SSI analysis should be consistent with the corresponding site response analysis for developing the FIRS.

5.3 Position on Minimum Foundation Input

As described in SRP Section 3.7.1 and required by Section IV(a)(1)(i) of Appendix S to 10 CFR Part 50, the horizontal component of the input motion should not be less than the suitable broad band spectrum scaled to 0.1g. The acceptance criteria in SRP Section 3.7.1 specify the following:

> The response spectrum associated with this minimum PGA should be a smooth broad-band response spectrum (e.g., RG 1.60, or other appropriately shaped spectrum if justified) considered as an outcrop response spectrum at the free-field foundation level. This response spectrum anchored at 0.1g will be referred to in this SRP section as the minimum required response spectrum.

The following procedure can be used to meet the minimum foundation input. The minimum foundation input ground motion for design shall be at least an appropriate broad band response spectrum with value 0.1g PGA. For all certified designs typically designed to a broad-band spectrum scaled to 0.30g, this check is not necessary. For the site-specific SSI analysis of Category I structures not covered by the certified design, the minimum requirement must be satisfied. For this evaluation, the FIRS used as the basis to develop the SSI input must be compared with the minimum motion. If the FIRS do not envelop the minimum spectra, the envelope of the FIRS and the minimum spectra should be used to develop the SSI input motion. Alternatively, the SSI analysis should be performed twice using the site-specific FIRS and the minimum spectra separately and enveloping the SSI responses. The three SSI soil profiles obtained from the generation of FIRS can be used for the SSI analysis. Consistent with Regulatory Position 5.2, “Vertical Spectrum,” of the RG 1.208 and common industry practice, the vertical spectrum should be developed using the appropriate V/H ratios. For vertical analysis, site-specific FIRS can be used.

5.4 Position on Documentation

The final safety analysis report (FSAR) for a COL application referenced in SRP Section 3.7.1 should include the following for the staff review and evaluation, with the exception that when the

FSAR contains the same information in Section 2.5.2, a reference to that information should be provided:

(a) a description of the soil column profile with iterated site-specific soil properties at the 10^{-4} mean annual frequency of exceedance level, including the strain-dependent shear modulus degradation curves and damping curves

(b) the V/H ground motion spectra across the entire spectral frequency range

(c) the best estimate, upper bound, and lower bound soil column properties for both horizontal and vertical site-specific ground motion

- site-specific FIRS for all safety-related structures and a description of how the PBSRS is enveloped when the FIRS is convolved to the free surface

- a description of how the minimum foundation-level seismic ground motion input criterion is met

- comparison of CSDRS to the site-specific seismic demand

- justification for acceptability in exceedance of the CSDRS by site-specific seismic ground motion demand in in-structure response spectra where applicable

References:

1. NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants,” NRC, March 2007, Sections 2.5.2, 3.7.1 and 3.7.2. (ADAMS Accession Nos. ML070730593, ML070640306, ML070640311).

2. ISG-01, “Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications,” NRC, June 12, 2009. (ADAMS Accession No. ML081400293).

3. NEI White Paper, “Consistent Site-Response/Soil-Structure Interaction Analysis and Evaluation,” NEI, June 12, 2009. (ADAMS Accession No. ML091680715).

4. BNL Report N6112-051208, Revision 1, “Consistent Site Response—SSI Calculations,” Carl J. Costantino, BNL, July 15, 2009. (ADAMS Accession No. ML091980384).

5. “Summary of September 25–26, 2008, Public Meeting/Workshop on Seismic Issues Consistent Site-Response-Soil-Structure Interaction Calculations,” NRC, October 24, 2008. (ADAMS Accession No. ML082950476).

6. 10 CFR Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants.”

7. RG 1.208, “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion,” NRC, March 2007.

8. NUREG/CR-6728, "Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk- Consistent Ground Motion Spectra Guidelines," NRC, October 2001.

9. 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities."

10. RG 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants," Revision 1, NRC, December 1973.

11. RG 1.206, "Combined License Applications for Nuclear Power Plants (LWR Edition)," NRC, June 2007.