U.S. NUCLEAR REGULATORY COMMISSION

DESIGN-SPECIFIC REVIEW STANDARD for NuScale SMR DESIGN

3.7.2 SEISMIC SYSTEM ANALYSIS

REVIEW RESPONSIBILITIES

Primary - Organization responsible for seismic and structural analysis reviews

Secondary - None

I. AREAS OF REVIEW

The specific areas of review are as follows:

1. Seismic Analysis Methods. For all seismic Category I structures, systems, and components (SSCs), the staff reviews the applicable seismic analysis methods (response spectrum analysis method, time history analysis method, or equivalent static load analysis method). The staff reviews the manner in which the dynamic system analysis is performed, including the modeling of foundation torsion and overall building rocking and translation. The review also includes modeling of the potential effects of kinematic interaction over the depth of the facility on dynamic system analysis. The modeling of soil-structure interaction (SSI) effects is reviewed. The staff reviews the method chosen for the determination of significant modes and an adequate number of discrete mass degrees of freedom. The staff also reviews the manner in which consideration is given in the seismic analysis to maximum relative displacements between supports. In addition, the staff reviews other significant effects that are accounted for in the seismic analysis, such as hydrodynamic effects and nonlinear analysis methods and responses. For each area of review, the staff selects representative locations and seismic response quantities of interest. If tests or empirical methods are used in lieu of analysis for any seismic Category I structure, the testing procedure, load levels, and acceptance basis are also reviewed. The Design-Specific Review Standard (DSRS) criteria generally deal with linear elastic analysis, coupled with allowable stresses near the elastic limits of the structures. However, for certain special cases (e.g., evaluation of as-built structures), the staff has accepted the consideration of limited inelastic/nonlinear behavior when appropriate. The staff conducts a detailed review of all inelastic/nonlinear analyses.

2. Natural Frequencies and Responses. The staff reviews the significant natural frequencies and responses (accelerations, displacements, and member forces) for all seismic Category I structures. In addition, the in-structure seismic response spectra at the support locations for seismic Category I subsystems are reviewed.

3. Procedures Used for Analytical Modeling. The staff reviews the criteria and procedures used in modeling the seismic system analyses (including structural material properties,

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modeling of member stiffness, modeling of mass (structural masses, live loads, floor loads, and equipment loads), modeling of damping, modeling of hydrodynamic effects, etc.). The staff also reviews the criteria and bases for determining whether a structure is analyzed as part of a structural system analysis or independently as a subsystem. In addition, the method used to address floor and wall flexibility in the structural modeling is reviewed.

4. <u>Soil-Structure Interaction</u>. Foundation input response spectra (FIRS) which is the ground motion response spectra at the foundation level are defined in the free field (i.e., without the presence of structures) as described in DSRS Section 3.7.1, DC/COL-ISG-01, "Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications," and DC/COL-ISG-017, "Interim Staff Guidance on Ensuring Hazard-Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses." For a deeply embedded structure, performance-based response spectra (PBRS) are also defined in the free field at the ground surface and appropriate intermediate depth(s) to ensure the adequacy of the soil columns used in the deterministic SSI analysis and to determine the potential magnitude of kinematic interaction effects on the structure over the depth of the facility. The FIRS and PBRS determined at the foundation level, surface, and intermediate depth(s) should be developed in a consistent manner. They are probabilistically determined performance-based spectra generated using the soil column corresponding to the building. The properties of the soil columns usually consist of 60 or more randomized sets of properties similar to those used in the probabilistic seismic hazard analysis (PSHA) process. For sites with soil layers near the surface that will be completely excavated to expose competent material and replaced with extended compacted backfill layers, the FIRS and PBRS are determined by considering the effect of the backfill layers in the site profiles. FIRS at the foundation and PBRS at intermediate levels should also be developed as free field outcrop motions, not as in-column motions. Competent material is generally considered to be in situ material having a minimum shear wave velocity of 1,000 fps.

   As applicable, the staff reviews the modeling methods (including technical bases) used in the seismic system analysis to account for SSI. The factors to be considered in accepting a particular modeling method include (1) the extent of embedment, (2) the layering of the soil/rock strata, and (3) the boundary of the soil-structure model. All SSI analyses should recognize the uncertainties prevalent throughout the phenomenon and include consideration of the following:

   A. The random nature of the soil and rock configuration and material characteristics.

   B. Uncertainty in soil constitutive modeling (soil stiffness, damping, etc.).

   C. Nonlinear soil behavior.

   D. Coupling between the structures and soil.

   E. Lack of lateral uniformity in the site soil profile that is usually assumed to be uniformly layered in all horizontal directions in SSI analyses.

F. Effects of the flexibility of soil/rock.

G. Effects of the flexibility of basemat, sidewalls, and interior structures.

H. The effect of pore water on structural responses, including the effects of variability of ground water level with time.

I. Effects of potential separation or loss of contact between the structure (embedded portion of the structure and foundation mat) and the soil during the earthquake.

J. For deeply embedded or fully buried structures, (1) the effect of deep embedment on the relative significance of kinematic interaction, (2) the extent to which nonvertically propagating shear waves may be more important for deeply embedded structures than for those with shallow embedment depth, (3) the impact of deep embedment on the accuracy of sidewall impedance functions calculated with standard methods, (4) the effect of nonlinear behavior (e.g., separation of structure and soil, and soil material properties) on wall pressure and SSI calculations, and (5) the variation of V/H (vertical to horizontal) spectral ratios on ground motion over the depth of the facility.

K. If incoherence effects to reduce high-frequency motions are included in the SSI response, the evaluation needs to include consideration of the potential variation of the Coherency Function described in DC/COL-ISG-01 with depth.

The staff reviews the procedures by which strain-dependent soil properties (damping, shear modulus, pore pressure development), layering, and variation of soil properties are incorporated in the analysis. Assumptions for modeling the soil-structure system and computer program validation documents are also reviewed.

If applicable, the criteria for determining the location of the bottom boundary and side boundary of the soil-structure system model are reviewed. The procedures used in the SSI analysis to account for effects of adjacent structures, if any, on structural response are reviewed.

To perform a seismic analysis for an SSI system, it may be necessary to have well-defined excitation or forcing functions applied at the model boundaries to simulate the design ground motion. It is therefore required in such cases to generate an excitation system acting at the boundaries, such that the response motion of the soil media at the plant site in the free field is identical to the design ground motion. The procedures and theories for regeneration of such an excitation system are reviewed.

Any other modeling methods used for SSI analysis are also reviewed, as is any basis for not using an SSI analysis.

For a DC application, the number and characteristics of generic site profiles are reviewed to ensure that there is an adequate seismic design basis for a standard plant.

5. Development of In-Structure Response Spectra. The procedures and methods for developing in-structure response spectra (ISRS) (e.g., floor response spectra) are reviewed. There are several methods for generating ISRS. One method makes use of time history analysis by considering single or multiple (real or artificial) ground motion time histories which have response spectra that satisfy the enveloping criteria for the design ground response spectra and the target power spectral density (PSD) function. A second method, which does not require time history analysis, is generally referred to as direct generation of ISRS. The basis and justification for the use of either of the above methods are reviewed.

6. Three Components of Design Ground Motion. The staff reviews the procedures by which the three components of design ground motion (time history or response spectra) are considered in determining the seismic response of all seismic Category I SSCs. If three design ground motion time histories (two horizontal and one vertical) are applied in a single time history analysis, the statistical independence among the three components is also reviewed.

7. Combination of Modal Responses. When a modal time history analysis method or a response spectrum analysis method is used to calculate the seismic response of SSCs, the staff reviews the contribution to the total response due to the effects of high-frequency modes to ensure that the total response closely simulates the behavior of the SSC during a seismic event. The high-frequency modes are those modes with natural frequencies greater than the frequency at which the spectral acceleration converges to approximately the zero period frequency, ZPA. When a response spectrum method is used, the procedure for combining modal responses, including modes with closely spaced frequencies, is reviewed.

8. Interaction of Non-Seismic Category I Structures with Seismic Category I SSCs. The staff reviews the specific design criteria to account for the seismic motion of non-seismic Category I structures (or portions thereof) in the seismic design of seismic Category I structures (or portions thereof). The staff also reviews the seismic design of structures whose continued function is not required but whose failure could adversely impact the intended safety function of a seismic Category I SSC, or result in incapacitating injury to control room occupants. In addition, the staff reviews any special design features employed to protect seismic Category I SSCs from the structural failure of non-seismic Category I structures due to seismic effects.

9. Effects of Parameter Variations on Floor Responses. The staff reviews the procedures that are used to consider the effects of the expected variations of structural properties, critical damping values, soil properties, and SSI on the floor response spectra and response time histories.

10. Use of Equivalent Vertical Static Factors. Where applicable, the staff reviews the justification for the use of equivalent vertical static load factors in calculating the vertical response loads for designing seismic Category I SSCs, in lieu of the use of a vertical seismic system dynamic analysis.

11. Methods Used to Account for Torsional Effects. The method employed to consider torsional effects in the seismic analysis of seismic Category I structures is reviewed.

The review includes evaluation of the conservatism of any approximate methods to account for torsional effects in the seismic analysis and the design of seismic Category I structures. The consideration of accidental torsion for calculating structural responses is also reviewed.

12. Comparison of Responses. Where applicable, the staff reviews the comparison of seismic responses for major seismic Category I structures using modal response spectrum and time history approaches.

13. Analysis Procedure for Damping. The procedure employed to account for different critical damping values in different elements of the system structural model is reviewed.

14. Determination of Seismic Overturning Moments and Sliding Forces, Structure to Soil Pressures and Frictional Forces for Seismic Category I Structures. The staff reviews the description of the method and procedure used to determine design seismic overturning moments and sliding forces, structure to soil pressures beneath the foundation and alongside walls (including potential sliding and separation effects), and soil friction for all seismic Category I structures.

15. Inspections, Tests, Analyses, and Acceptance Criteria (ITAAC). For DC and COL reviews, the staff reviews the applicant's proposed ITAAC associated with the SSCs (if any are identified related to this DSRS section) in accordance with NUREG-0800 Standard Review Plan (SRP) Section 14.3, "Inspections, Tests, Analyses, and Acceptance Criteria." The staff recognizes that the review of ITAAC cannot be completed until after the rest of this portion of the application has been reviewed against acceptance criteria contained in this DSRS section. Furthermore, the staff reviews the ITAAC to ensure that all SSCs in this area of review are identified and addressed as appropriate in accordance with SRP Section 14.3.

16. COL Action Items and Certification Requirements and Restrictions. For a DC application, the review also addresses COL action items, requirements, and restrictions (e.g., interface requirements and site parameters).

    For a COL application referencing a DC, the COL applicant must address COL action items (referred to as COL license information in certain DCs) included in the referenced DC. Additionally, the COL applicant must address requirements and restrictions (e.g., interface requirements and site parameters) included in the referenced DC.

As part of the review activities, the staff conducts onsite audits. The purpose of these audits is to review technical information and detailed calculations not submitted as part of the license or certification application, and to review additional information needed to resolve open technical issues. See Appendix A of this DSRS section for general guidelines on conducting audits.

Review Interfaces

Other SRP and DSRS sections interface with this section as follows:

1. Review of geological and seismological information to establish the free field ground motion over the complete depth of the embedded facility is performed under SRP Sections 2.5.1 through 2.5.3.

2. The geotechnical parameters and methods employed in the analysis of free field and onsite soil media and soil properties are reviewed under SRP Section 2.5.4.

3. The design ground motion (response spectra and time histories) and supporting media (soil profiles) are reviewed under DSRS Section 3.7.1.

4. Seismic subsystem analysis is reviewed under DSRS Section 3.7.3. This includes, but is not limited to, seismic Category I substructures, such as platforms, frame support structures, yard structures; buried piping, tunnels, and conduits; concrete dams; and atmospheric storage tanks.

5. The design of seismic Category I structures for all applicable load combinations is reviewed under DSRS Sections 3.8.4, and 3.8.5.

6. For DC applications, the staff reviews the applicant's proposed site parameters in Tier 1 of the Design Control Document (DCD) and in Chapter 2 of Tier 2 of the DCD in accordance with the guidance in SRP Section 2.0, "Site Characteristics and Site Parameters." For COL applications referencing a DC, the staff reviews the applicant's site characteristics in COL application final safety analysis report (FSAR) Section 2.0 in accordance with the guidance in SRP Section 2.0, "Site Characteristics and Site Parameters."

7. Review of the Seismic Probabilistic Risk Assessment is performed under SRP Section 19.0 in conjunction with DC/COL-ISG-20, "Interim Staff Guidance on Implementation of a Probabilistic Risk Assessment-Based Seismic Margin Analysis for New Reactors," for potential risk significance of SSCs and the risk-based susceptibility of risk-significant SSCs to failure due to seismic hazards.

The review of the design ground motion (safe shutdown earthquake (SSE), certified seismic design response spectra (CSDRS), operating basis earthquakes (OBE), if applicable); the generic-site or site-specific soil properties; and the SSI analyses is an integral part of the overall review process for seismic Category I structures.

II. ACCEPTANCE CRITERIA

Requirements

Acceptance criteria are based on meeting the relevant requirements of the following Commission regulations:

1. Appendix A to 10 CFR Part 50, GDC 2—The design basis shall reflect appropriate consideration of the most severe earthquakes that have been historically reported for the site and surrounding area with sufficient margin for the limited accuracy, quantity, and period of time in which historical data have been accumulated.

2. Appendix S, “Earthquake Engineering Criteria for Nuclear Power Plants,” to 10 CFR Part 50, is applicable to applications for a DC or COL under 10 CFR Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants,” or a CP or OL pursuant to 10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities,” on or after January 10, 1997. Appendix S requires that, for SSE ground motions, certain SSCs will remain functional and within applicable stress, strain, and deformation limits. The required safety functions of these SSCs must be assured during and after the vibratory ground motion associated with the SSE ground motion through design, testing, or qualification methods. The evaluation must take into account SSI effects and the expected duration of the vibratory motion. If the OBE is set at one-third or less of the SSE, an explicit response or design analysis is not required. If the OBE is set at a value greater than one-third of the SSE, an analysis and design must be performed to demonstrate that, when subjected to the effects of the OBE in combination with normal operating loads, all SSCs of the nuclear power plant (NPP) necessary for continued operation without undue risk to the health and safety of the public remain functional and within applicable stress, strain, and deformation limits. Appendix S also requires that the horizontal component of the SSE ground motion in the free field at the foundation level of the structures must be an appropriate response spectrum with a peak ground acceleration (PGA) of at least 0.1g.

3. In 10 CFR 52.47(b)(1), the NRC requires that a DC application contain the proposed ITAAC that are necessary and sufficient to provide reasonable assurance that, if the inspections, tests, and analyses are performed and the acceptance criteria met, a facility that incorporates the DC has been constructed and will be operated in conformity with the DC, the provisions of the Atomic Energy Act of 1954, as amended (AEA), and the Commission’s rules and regulations.

4. In 10 CFR 52.80(a), the NRC requires that a COL application contain the proposed inspections, tests, and analyses, including those applicable to emergency planning, that the licensee shall perform, and the acceptance criteria that are necessary and sufficient to provide reasonable assurance that, if the inspections, tests, and analyses are performed and the acceptance criteria met, the facility has been constructed and will operate in conformity with the COL, the provisions of the AEA, and the Commission’s rules and regulations.

DSRS Acceptance Criteria

Specific DSRS acceptance criteria acceptable to meet the relevant requirements of the NRC’s regulations identified above are set forth below. The DSRS is not a substitute for the NRC’s regulations, and compliance with it is not required. As an alternative, and as described in more detail below, an applicant may identify the differences between a DSRS section and the design features (DC and COL applications only), analytical techniques, and procedural measures proposed in an application and discuss how the proposed alternative provides an acceptable method of complying with the NRC regulations that underlie the DSRS acceptance criteria.

1. <u>Seismic Analysis Methods</u>. The seismic analysis of all seismic Category I SSCs should use either a suitable dynamic analysis method or an equivalent static load analysis method, if justified. The DSRS acceptance criteria primarily address linear elastic analysis coupled with allowable stresses near elastic limits of the structures. However, for certain special cases (e.g., stability analyses and evaluation of as-built structures), reliance on limited inelastic/nonlinear behavior is acceptable to the staff when appropriate. Analysis methods incorporating inelastic/nonlinear considerations and the analysis results are reviewed on a case-by-case basis.

   A. <u>Dynamic Analysis Method</u>. When calculating seismic responses of seismic Category I structures, dynamic analysis (response spectrum analysis method or time history analysis method) should be performed. To be acceptable, dynamic analyses should consider the following:

      i. Use of appropriate methods of analysis (time history analysis method (time domain solution and frequency domain solution); response spectrum analysis method) to account for the effects of SSI, if applicable. In general, the response spectrum analysis method is not suitable for SSI analysis.

      ii. Seismic analysis should be performed for three orthogonal (two horizontal and one vertical) components of design ground motion.

      iii. Consideration of the torsional, rocking, and translational responses of the structures and their foundations (including footings, basemats, and buried walls).

      iv. Use of an adequate number of discrete mass degrees of freedom in dynamic modeling.

      The adequacy of the number of discrete mass degrees of freedom can be confirmed by (1) preliminary modal analysis and (2) correlation between static analysis results using the dynamic model and static analysis results using a distributed mass representation.

         (1) It is important to ensure that, for each excitation direction (two horizontal and one vertical), all modes with frequencies less than the ZPA frequency of the corresponding input spectrum are adequately represented in the dynamic solution. Preliminary modal analysis should be performed to establish that a sufficient number of discrete mass degrees of freedom have been included in the dynamic model to (a) predict a sufficient number of modes and (b) produce mode shapes that are reasonably smooth. If a mode shape exhibits rapid change in modal displacement between adjacent mass degrees of freedom, additional mass degrees of freedom should be added until reasonably smooth mode shapes are obtained for all modes to be included in the dynamic analysis.

(2) After completion of (1), simple 1g static analyses of the dynamic model should be performed for each of the three excitation directions and compared to the corresponding results obtained from static analyses that utilize a distributed mass representation. Lack of correlation, particularly in the vicinity of and at support locations, is indicative of an insufficient number of discrete mass degrees of freedom.

v. When using either the response spectrum method or the modal superposition time history method, responses associated with high-frequency modes (i.e., f ≥ ZPA (or PGA) frequency) should be included in the total dynamic solution using the guidance and methods described in RG 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis."

vi. Consideration of maximum relative displacements between adjacent supports of seismic Category I SSCs.

vii. Inclusion of significant effects such as piping interactions, externally applied structural restraints, hydrodynamic (both mass and stiffness effects) loads, and nonlinear responses.

B. Equivalent Static Load Method. An equivalent static load method is acceptable if:

i. Justification is provided that the system can be realistically represented by a simple model and the method produces conservative results in terms of responses. Typical examples or published results for similar structures may be submitted in support of the use of the simplified method.

ii. The simplified static analysis method accounts for the relative motion between all points of support and incorporates the potential effects of kinematic interaction over the depth of the facility.

iii. To obtain an equivalent static load for an SSC that can be represented by a simple model, a factor of 1.5 is applied to the peak spectral acceleration of the applicable ground or floor response spectrum. A factor less than 1.5 may be used, if adequate justification is provided.

2. Natural Frequencies and Responses. To be acceptable, the following information should be provided:

A. A summary of modal masses, effective masses, natural frequencies, mode shapes, and modal and total responses for the seismic Category I structures (including the reactor power module) or a summary of the total responses if the method of direct integration is used.

B. The seismic input motions (e.g., time histories, response spectra, displacements, etc.) in two horizontal directions and one vertical direction at the major plant equipment elevations and points of support.

C. For the multiple time history analysis option, procedures used to account for uncertainties (by variation of parameters) and to develop design responses. The application should also include a justification for the statistical relationship between input design time histories and output responses. (For example, if the average response spectra generated from the multiple design time histories are used to envelop the design response spectra, then the average responses generated from the multiple analyses should be used in the design.)

3. Procedures Used for Analytical Modeling. A nuclear power plant (NPP) facility consists of very complex structural systems. To be acceptable, the stiffness, mass, and damping characteristics of the structural systems should be adequately incorporated into the analytical models. Specifically, the following items should be considered in analytical modeling:

A. Designation of Systems versus Subsystems. Seismic Category I structures that are considered in conjunction with the foundation and its supporting media are defined as “seismic systems.” Other seismic Category I SSCs that are not designated as “seismic systems” should be considered as “seismic subsystems.”

B. Decoupling Criteria for Subsystems. It can be shown, in general, that frequencies of systems and subsystems have a negligible effect on the error due to decoupling. It can be shown that the mass ratio, R_m, and the frequency ratio, R_f, govern the results where R_m and R_f are defined as:

$$R_m = \frac{\text{Total mass of the supported subsystem}}{\text{Total mass of the supporting system}}$$

$$R_f = \frac{\text{Fundamental frequency of the supported subsystem}}{\text{Dominant frequency of the support motion}}$$

The following criteria are acceptable:

i. If $R_m < 0.01$, decoupling can be done for any R_f.

ii. If $0.01 \leq R_m \leq 0.1$, decoupling can be done if $R_f \leq 0.8$ or $R_f \geq 1.25$.

iii. If $R_m > 0.1$, a subsystem model should be included in the primary system model.

If the subsystem is rigid compared to the supporting system, and also is rigidly connected to the supporting system, it is sufficient to include only the mass of the subsystem at the support point in the primary system model. On the other hand, in case of a subsystem supported by very flexible connections (e.g., pipe supported by hangers), the subsystem need not be included in the primary model. In most cases, the equipment and components, which come under the definition of subsystems, are analyzed (or tested) as a decoupled system from the primary structure, and the seismic input for the former is obtained by the analysis of the latter. One important exception to this procedure is the reactor coolant system, which is considered a subsystem but is usually analyzed using a coupled model of the reactor coolant system and primary structure.

C. Modeling of Structures. Two types of structural models are widely used by the nuclear industry: the lumped-mass stick model and the finite element model. Either of these two types of modeling techniques is acceptable if the following guidelines are met:

i. Lumped-Mass Stick Model

For a lumped-mass model, the eccentricities between the centroid (the neutral axis for axial and bending deformation), the center of rigidity (the neutral axis for shear and torsional deformation), and the center of mass of structures should be included in the seismic model.

The acceptance criteria given in Subsection II.1.A.iv of this DSRS section are acceptable for selecting an adequate number of discrete mass degrees of freedom in the dynamic modeling to determine the response of all seismic Category I and applicable non-seismic Category I structures.

Ground motion input to the lumped-mass stick model should be consistent with the FIRS as described in DSRS Section 3.7.1.

ii. Finite Element Model

The type of finite element used for modeling a structural system should depend on the structural details, the purpose of the analysis, and the theoretical formulation upon which the element is based. The mathematical discretization of the structure should include consideration of the effect of element size, shape, and aspect ratio on solution accuracy. The element mesh size should be selected on the basis that further refinement has only a negligible effect on the solution results.

iii. In developing either a lumped-mass stick model or a finite element model for dynamic response, it is necessary to consider that local regions of the structure, such as individual floor slabs or walls, may have fundamental vibration modes that can be excited by the dynamic seismic loading. These local vibration modes should be adequately represented in the dynamic response model, in order to ensure that the ISRS include the additional amplification. Also, the additional seismic loading on the overall structure and on the local region is needed for detailed structural design.

In general, three-dimensional models should be used for seismic analyses. However, simpler models can be used if the coupling effects of those degrees of freedom that are omitted from the three-dimensional models are not significant.

iv. Modeling of the appropriate stiffness and damping for the various structural elements in the mathematical model is essential to obtain realistic seismic responses (e.g., ISRS, building accelerations, member forces, and displacements). For reinforced concrete structures, the stiffness used in the model depends on the degree of concrete cracking, which is a function of the level of stress due to the most critical load combination. The effects of concrete cracking on membrane, bending, and shear stiffness should be considered as appropriate in the mathematical model. Because the effect of cracking on the stiffness of concrete members is complex and depends on a number of factors, the approach used should be shown to be conservative. One approach for considering the cracked concrete properties is to reduce the stiffness properties of the uncracked members by a reduction factor. Acceptable stiffness reduction factors for cracked concrete members are given in American Society of Civil Engineers / Structural Engineering Institute (ASCE/SEI) 43-05 (e.g., 0.5 for cracked walls for flexure and shear).

If structural responses (e.g., member forces, displacements, soil bearing pressures) are determined from a separate detailed finite element analysis (what is referred to as a two-step approach), the effects of concrete cracking should be considered both in the SSI analysis and the detailed structural analysis.

Further guidance on consideration of concrete cracking in the analysis and design of seismic Category I structures is provided in the acceptance criteria for design and analysis procedures presented in DSRS Sections 3.8.4 and 3.8.5.

For the generation of ISRS, the guidance given below should be followed.

For a generic design, the cracked concrete properties and the associated SSE damping values in Table 1 of RG 1.61, “Damping Values for Seismic Design of Nuclear Power Plants,” can be used if the design-basis ISRS represent the envelope of the in-structure responses obtained from multiple analyses conducted to consider the range of expected site soil conditions associated with the CSDRS. If a CSDRS is associated with a single site condition, such as the hard rock high-frequency (HRHF) spectra for a specific site, then it is acceptable to use uncracked concrete properties with the OBE damping values in Table 2 of RG 1.61 to develop the ISRS.

For site-specific designs, where it is not desirable to utilize the approach described above, a seismic analysis can be performed based on the best estimates of the stiffness properties of the structural members. A mathematical model of the structure should be developed to be representative of the structure and analyzed for the uncracked stiffness properties. The analysis may be performed by assuming, for shear walls as an example, in-plane bending and shear stiffness values corresponding to the uncracked properties, and a damping value of 4 percent. After performing the seismic analysis, the calculated state of stress in the concrete members should be compared to the stresses that would cause cracking, for all load combinations that include seismic effect. If extensive cracking is determined based on this stress comparison, then the stiffness of those members should be reduced (e.g., using stiffness reduction factors). In other regions of the model where cracking does not occur, the same uncracked properties should be used, and the seismic analysis should be rerun. For those regions that are cracked, 7-percent damping may be used, while 4-percent damping should be used for the uncracked regions. The results of this analysis may be used as the basis for the ISRS, provided there are no additional members whose state of stress leads to further significant cracking in the model. If further significant cracking is identified in some of the remaining uncracked members, then reductions in the stiffness representation of those members should be made and a re-analysis of the model performed. If the state of stress in any cracked members demonstrates that the cracked members are no longer cracked, then it is not necessary to revise the cracked member properties back to the original uncracked properties.

If any alternative methods are utilized, then adequate justification needs to be provided to demonstrate that the best estimate stiffness properties used for concrete are appropriate and that uncertainty associated with the best estimate stiffness values have been considered. In addition, it should be demonstrated that the SSI frequencies in both the horizontal and vertical directions are sufficiently below the amplified portion of the input design spectra so that if further cracking were to occur, then any reduction in stiffness would not increase the seismic demand. If the SSI frequencies are located above the amplified portion of the input design response spectra, then the analysis needs to evaluate the effects of further concrete cracking since this may lead to higher demand loads on the structure.

D. Representation of Floor Loads, Live Loads, and Major Equipment in Dynamic Model. In addition to the structural mass, a mass equivalent to a floor load of 50 pounds per square foot should be included to represent miscellaneous dead weights such as minor equipment, piping, and raceways. Also, a mass equivalent to 25 percent of the floor design live load and 75 percent of the roof design snow load, as applicable, should be included. The mass of major equipment should be distributed over a representative floor area or included as concentrated lumped masses at the equipment locations.

E. Special Consideration for Dynamic Modeling of Structures. It has been common practice that the dynamic model used to predict the seismic response of a structure is not as detailed as the structural model used for the detailed design analysis of all applicable load combinations. Therefore, a methodology is needed to transfer the seismic response loads determined from the dynamic model to the structural model used for the detailed design analysis of all applicable load combinations. This is reviewed for technical adequacy on a case-by-case basis.

4. <u>Soil-Structure Interaction</u>. A complete SSI analysis should properly account for all SSI effects (e.g., effects due to kinematic and inertial interaction, as applicable) for surface or embedded structures. Any analysis method based on either a direct approach or a substructure approach can be used provided the following conditions are met:

   A. The structure, foundation, and soil are properly modeled to ensure that the results of analyses properly capture spatial variation of ground motion, three-dimensional effects of radiation damping and soil layering, as well as nonlinear effects from site response analyses. The analyses need to incorporate the appropriate soil profiles determined in accordance with SRP Sections 2.5.1 through 2.5.3, as well as DSRS Section 3.7.1.

   B. For structures with either surface or shallow embedded foundations, the seismic input motions to the SSI analyses can be typically placed at the free ground surface or at the foundation level using the guidance in DSRS Section 3.7.1, as supplemented by DC/COL-ISG-017. However, the input motions defined at locations other than the foundation level may not be appropriate for deeply embedded structures. In these situations, the seismic input should be specified only at the foundation level as the FIRS.

   For deeply embedded or buried structures, proper consideration should be given to uncertainties associated with kinematic interaction, non-vertically propagating shear waves, sidewall impedance calculation, and other effects such as the development of gaps between the soil and structure (specifically for strong motion earthquakes). For non-vertically propagating shear waves, a sensitivity evaluation can be performed to determine whether this is an important effect to be included in the SSI analysis.

   The staff has sufficient confidence that the current SSI analysis methods capture the basic SSI phenomenon and provide adequate design information. However, in order to ensure proper implementation of the method, the following considerations should be addressed in the SSI analysis:

   A. Perform sensitivity studies to identify important parameters (e.g., potential separation and sliding of soil from sidewalls, nonsymmetry of embedment, location of boundaries, and foundation uplift if applicable) and to assist in judging the adequacy of the final results. These sensitivity studies can be performed by the use of well-founded and properly substantiated simple models to give better insight.

   B. Through the use of some appropriate benchmark problems, the user should demonstrate its capability to properly implement any SSI methodologies.

C. Perform enough parametric studies with the proper variation of parameters (e.g., soil properties) to address the uncertainties (as applicable to the given site) discussed in Subsection I.4 of this DSRS section.

The effect of the foundation uplift should be evaluated if the SSI analysis using linear techniques results in net tension stresses between the foundation basemat and the underlying soil, for load combinations that include seismic, dead and other applicable gravity loads (per DSRS Section 3.8.5 II.4.D uplift evaluations). The staff reviews the calculation of the ground contact ratio to ensure the linear SSI analysis remains valid. The ground contact ratio is defined as the minimum ratio of the area of the foundation in contact with the soil to the total area of the foundation, computed in each time step throughout the SSI analysis.

Uplift for nonsymmetric structures may be more affected by the phasing between the three directions of input motions. Therefore, technical justification should be provided if the effect of different phasing of the input motions is not considered in the calculation of the foundation uplift. If the nonsymmetric conditions need to be addressed, then the effect of in-phase and out-of-phase input motions can be considered in the SSI analyses by using plus and minus 1.0 times the magnitude of the input motions.

Linear SSI analysis methods are acceptable if the ground contact ratio is equal to or greater than 80 percent. The ground contact ratio can be calculated from the linear SSI analysis using the minimum basemat area that remains in compression with the soil. If the ratio is less than 80 percent, then the effect of the nonlinearity due to the foundation uplift should be evaluated. If the uplift effect on structural responses (e.g., ISRS, member forces, soil bearing pressure, and building displacements) is found to be significant (e.g., an increase in response of more than 10 percent), then the uplift effect should be accounted for in the seismic design. Accounting for the uplift effect in these cases is reviewed on a case-by-case basis.

While uplift of deeply embedded structures is not expected, uplift for surface mounted and shallow embedded structures is a concern that should be evaluated.

The acceptance criteria for the constituent parts of the entire SSI system are summarized as follows:

A. <u>Modeling of Structure</u>. The acceptance criteria given under Subsection II.3 of this DSRS section are applicable.

B. <u>Modeling of Supporting Soil</u>. The effects of structure embedment, ground water, placement of compacted fills, and soil layering should be accounted for. For modeling of the supporting soil media, the compliance function methods are acceptable provided that frequency variations and layering effects are incorporated. For the method of modeling soil media with finite boundaries, all boundaries should be properly simulated and the use of types of boundaries should be justified and reviewed on a case-by-case basis. Finite element and finite difference methods are acceptable methods for discretization of a continuum. The properties used in the SSI analysis should be those that are consistent with soil strains developed in free field site response analyses. Typical lumped parameter methods sometimes accepted for SSI analysis of near-surface structures would not be expected to be appropriate without justification and without consideration of depth effects.

For structures founded on materials having a shear wave velocity of 8,000 fps or higher, under the entire surface of the foundation, a fixed base assumption is acceptable provided that variations in input motion over the depth of the embedment is accommodated in the SSI analyses.

In the SSI analysis of embedded structures using the substructure approach, the finite element discretization of the excavated soil volume should have a mesh size in both the horizontal and vertical directions that is appropriate for adequately transmitting seismic motions over the frequency range of interest. Both the horizontal and vertical mesh size for the excavated soil model should satisfy the wavelength requirement regardless of whether the model is being analyzed for the horizontal or vertical excitation. The geometric regularity of the mesh (aspect ratio and size) is also an important characteristic of the mesh to ensure the adequacy of the computational capability.

C. Input Ground Motion. The acceptance criteria for generating the input ground motion to be used in the SSI analysis are summarized in the following:

i. For structures with either surface or shallow embedded foundations, the seismic input motions to the SSI analyses can be placed at the free ground surface or at the foundation level. For deeply embedded structures, the seismic input should be specified at the foundation level as FIRS. In developing the corresponding ground motions at the surface and intermediate depth(s) in the soil profile, the potential effects of soft soil layers and/or compacted backfill layers need to be considered.

ii. Deterministic site response analyses are performed using at least three soil profiles defined as the Best Estimate (BE), Lower Bound (LB) and Upper Bound (UB) determined at the mean, with plus or minus one sigma iterated velocity/damping profiles generated from the set of at least 60 randomized profiles used in the PSHA response evaluations. The UB high-stiffness profile should make use of the LB damping properties for each layer of the profile. Similarly, the LB soft-stiffness profile should make use of the higher damping properties. The profiles used should be consistent with those used in the PSHA evaluation, except that for those cases where backfill is used to replace unacceptable soils in the profile, the backfill properties should be used provided the backfill layers are shown to be extensive enough to be consistent with the one-dimensional free field site response analyses. In addition, to ensure that the UB and LB profiles generated from the site-specific randomized set of profiles include an adequate range of variability, the layer velocities may need to be modified to ensure they possess the minimum coefficient of variation (COV) as discussed below under “Specific Guidelines for SSI Analysis.”

iii. Using the FIRS as input to each of the deterministic soil profiles, the envelope of the computed response spectra at the ground surface and intermediate depth(s) should be shown to exceed the mean spectra (PBRS) at these depths at all frequencies of interest.

Specific Guidelines for SSI Analysis

The following specific guidelines are provided here to facilitate the review and draw the attention of reviewers to some important aspects of the SSI analysis. These guidelines are not necessarily requirements for the acceptance of any methodologies or an SSI analysis.

- The behavior of soil, though recognized to be nonlinear, can often be approximated by linear techniques. Truly nonlinear analysis is not required unless the comparison of results from large-scale tests or actual earthquakes and analytical results indicate deficiencies that cannot be accounted for in any other manner. The nonlinear soil behavior may be accounted for by one of the following:

    - Using equivalent linear soil material properties typically determined from an iterative linear analysis of the free field soil deposit. This accounts for the primary nonlinearity.

    - Performing an iterative linear analysis of the coupled soil-structure system. This accounts for the primary and secondary nonlinearities.

  In the event the nonlinear analysis is chosen, the results of the nonlinear analysis should be judged on the basis of the linear or equivalent linear analysis (NUREG/CP-0054, “Proceedings of the Workshop on Soil-Structure Interaction”).

- Superposition of horizontal and vertical responses as determined from separate analyses is acceptable (assuming nonlinear effects are not important) considering the simple material models now available.

- The strain-dependent soil properties (e.g., shear modulus, damping) estimated from analysis of the seismic motion in the free field should be consistent with the geotechnical information reviewed under SRP Section 2.5.4.

- For a COL application referencing a standard plant design, the standard design SSI analysis is used if the site-specific FIRS are enveloped by the standard plant CSDRS determined at the foundation level. However, it is necessary to confirm that the site-specific, strain-dependent soil properties, including consideration of uncertainty, are consistent with the generic site profiles used in the standard plant design. If this is not the case, then a site-specific SSI analysis is needed.

- Enough SSI analyses should be performed to account for the effects of the potential variability in the properties of the soils and rock at the site. At least three soil/rock profiles should be considered in these analyses, namely, a BE profile, an LB profile and a UB profile. The properties of each layer of the site profile are typically defined in terms of its low-strain shear modulus and strain-dependent modulus degradation and strain-dependent hysteretic damping properties. These may be determined from dynamic laboratory testing of the site materials, information obtained from the published literature, or both. The set of properties appropriate for a given soil is reviewed for its adequacy. Guidance is also provided in DC/COL-ISG-017.

- For a particular site, the iterated shear modulus and damping values are typically determined from the results of a number of free field site response analyses, which are intended to account for the effects of the site-specific design ground motions as well as the site nonlinear properties. If only a single site response calculation is performed, with the low strain property of each material layer selected at its BE value, the resulting iterated property is then determined. The upper and lower bound values of soil/rock shear modulus (G) can then be defined in terms of their best estimate values as:

  $$G_{LB} = G_{BE} / (1+COV)$$

  $$G_{UB} = G_{BE} \times (1+COV)$$

  where COV is the coefficient of variation considered appropriate for the site materials. The corresponding damping properties should be defined at the compatible strains associated with the shear moduli.

  If many site response calculations are performed (60 or more site response calculations) using Monte Carlo techniques to develop site properties, these calculations are typically used to determine the BE, LB, and UB iterated site properties. The BE properties are determined from the mean of the resulting properties and the UB and LB values selected from the plus or minus one sigma values. Guidance for the site response analysis is provided in SRP Section 2.5.2.

  For well-investigated sites (see RGs 1.132, “Site Investigations for Foundations of Nuclear Power Plants,” and 1.138, “Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants”), the COV should be no less than 0.5. For sites that are not well-investigated, the COV for shear modulus should be at least 1.0. These COV requirements apply to the “single site response calculation,” as well as the “many site response calculations” described above. In no case should the lower bound shear modulus cause greater foundation settlement (based on standard foundation analysis) than that under static loads. The upper bound shear modulus should not be less than the best estimate shear modulus defined at low strain and as determined from the geophysical testing program. In no case should the material soil damping as expressed by the hysteretic damping ratio exceed 15 percent

(NUREG/CR-1161, “Recommended Revisions to Nuclear Regulatory Commission Seismic Design Criteria”).

For the case of analyses using generic broad-banded ground motion spectra, the best estimate shear modulus and damping of each material of the site profile can be defined in terms of its low strain values. The upper and low bound shear moduli can then be defined at twice and one-half the best estimate values, with damping maintained at its low strain value. Alternate approaches can be reviewed on a case-by-case basis.

- For a DC application, the postulated site profiles to be used in the seismic SSI analysis should be defined. The CSDRS should be shown to be appropriate for these postulated site profiles in frequency content by demonstrating that the frequencies for the amplified portion of the CSDRS are consistent with the site profile column frequencies. Otherwise, the postulated site profiles will not be able to propagate the CSDRS in the SSI analysis and, thereby, will not subject the SSCs to the amplified response over the frequency range of interest to the SSI.

- For dipping soil and rock strata, it is necessary to account for the coupling between the horizontal and vertical degrees of freedom in the stiffness and free field seismic motion definitions. Also, there may be sites where the reactor building or a seismic Category I structure may have an embedded foundation close to an embankment or a natural slope that precludes the assumption of uniform foundation condition. For such sites, modeling and analysis techniques are reviewed on a case-by-case basis.

- Finite Boundary Modeling or Direct Solution Technique

  The direct solution method is characterized as follows:

  - Each analysis of the soil and structures is performed in one step.

  - Finite element or finite difference discrete methods of analysis are used to spatially discretize the soil-structure system.

  - Definition of the motion along the boundaries of the model (bottom and sides) is either known, assumed, or computed as a precondition of the analysis.

  Dynamic analysis can be performed using either frequency-domain (limited to linear analysis) or time-integration methods. The mesh size should be adequate for representing the static stress distribution under the foundation and transmitting the frequency content of interest.

  The following limitations should be observed for deep soil sites:

- The model depth, generally, should be at least twice the base dimension below the foundation level, which should be verified by parametric studies.

- All structural modes of significance should be included.

- Half Space or Substructure Solution Technique

  The half space or substructure approach generally comprises the following steps:

  (1) Determine the motion of the massless foundation, including both translational and rotational components.

  (2) Determine the foundation stiffness in terms of frequency dependent impedance functions.

  (3) Perform SSI analysis.

  The procedures, modeling assumptions, and analytical bases adopted for performing the half space or substructure analysis are reviewed on a case-by-case basis.

  In the SSI analysis of embedded structures, some computer implementations of the substructure approach use two alternative methods to model the excavated soil volume:

  (1) In the direct method (DM), the excavated soil volume is modeled as discretized finite elements. In this method, the foundation impedance is calculated for the free field at all nodes of the discretized excavated soil volume. These nodes, termed "interaction nodes," connect the excavated soil volume and the free field soil system to ensure compatible motions. DM is also referred to as the flexible volume method (FVM) in frequency domain solutions.

  (2) In the Subtraction Method (SM), a simplification is made such that only the nodes on the outer boundaries of the excavated soil volume are treated as interaction nodes. This simplification reduces the computational effort needed for solving large problems typically encountered in NPP applications. However, because the interior nodes are not treated as interaction nodes, the compatibility of displacements is no longer imposed at every interaction node in the excavated volume. This may lead to limitations in applying the SM and to potential errors in computed foundation compliance functions as well as transfer functions.

  In light of the above discussion, the DM should be used to the extent practical to perform the SSI analysis of embedded structures. In cases that require the use of the SM, due to limitations of the DM in handling very large computational models, technical justifications should be provided to demonstrate the adequacy of the SSI analysis based on the SM. These technical justifications should include the following elements:

(1) An assessment of the excavated soil volume should be performed to identify its vibratory frequencies and mode shapes. These frequencies and mode shapes may be spurious in the SM solution, which can lead to nonconservative or erroneous results. They can be identified as spikes in the transfer functions computed using the SM, which do not appear in the corresponding transfer functions computed using the DM.

(2) The limitations of the SM can be mitigated by constraining sufficient interior nodes (as interaction nodes) of the excavated soil volume. This approach is known as the extended or Modified Subtraction Method (MSM). The effect of these additional constraints is to shift the frequencies of the spurious vibration modes above the frequency range of interest to the SSI analysis.

(3) A converging trend in the MSM solution may be established by carefully examining the computed transfer functions. The additional interaction nodes should shift the frequencies of the spurious spikes in the transfer functions above the frequencies of interest to the SSI analysis.

(4) An evaluation should be performed to ensure that the frequency content of the ground motion input important to the SSI analysis lies within a range that is minimally affected by the spurious vibration modes of the constrained excavated soil volume.

Computer models of reduced size (e.g., quarter models) can also be used to obtain additional insight into the adequacy of an SSI analysis performed using the SM/MSM. In this case, direct comparisons between the SM/MSM and DM solutions are feasible and may provide valuable information that could be extrapolated to the full-size model. Alternate methods may be used to assess the accuracy of the SM or MSM; such alternate methods are reviewed on a case-by-case basis.

There are advanced analytical methods which incorporate the effect of ground motion incoherency to develop seismic responses to high-frequency ground motion inputs. These methods might be used when a site acceptability determination is performed, as discussed in Subsection II.4 of DSRS Section 3.7.1. The phenomenon of ground motion incoherency in the free field has been investigated and characterized in terms of coherency functions that are based on recorded earthquake data collected from dense array field tests. The ground motion incoherency effect on structural response is considered by incorporating coherency functions in analytical methods for SSI analyses. SSI analyses based on analytical methods that consider ground motion incoherency generally reduce structural response in high frequencies, as compared to the response based on the traditional assumption of ground motion coherency. If the effect of incoherent ground motion is used to reduce the high-frequency response, the potential effects of incoherent ground motion in increasing overturning and torsional responses need to be considered.

The NRC issued DC/COL-ISG-01 on May 19, 2008, describing methods acceptable to the staff for evaluating high-frequency ground motion input. It includes guidance for conducting analyses that incorporate incoherent ground motion.

Because of the complexity of such analyses and the lack of both an experience database and test data, the implementation of the analytical methods described in DC/COL-ISG-01, for considering incoherent ground motion, is subject to staff review on a case-by-case basis. Applicants are expected to present comparisons between calculated coherent and incoherent seismic demands. Based on the staff's current experience, the following maximum reductions in the amplitude of spectral accelerations are acceptable for the ISRS:

- 0 to 10 Hz – 0-percent reduction
- 30 Hz and above – 30-percent reduction
- 10 to 30 Hz – reduction based on linear variation between 0 percent at 10 Hz and 30 percent at 30 Hz

The maximum ISRS reduction limits are applied to the calculated incoherent ISRS results only where the reduction limits are exceeded by the calculated reductions. Where the reduction limits are not exceeded, the calculated incoherent ISRS results are to be used, including where the incoherent results exceed the coherent results. The corresponding adjusted incoherent ISRS results are to be included in the ISRS comparison plots described above.

Larger ISRS reductions than specified above may be acceptable to the staff, if there is sufficient technical information supporting the larger reductions. The staff reviews and accepts the technical justifications for larger reductions on a case-by-case basis.

For structural loads, which are predominantly controlled by seismic input up to 10 Hz, the maximum acceptable reduction, due to the effects of incoherent ground motion, is 10 percent. If the structural loads increase due to the effects of incoherent ground motion, then the higher incoherent structural loads are to be used for structural design.

It is noted that the effects of incoherent ground motion may be considered at the DC application stage in a generic evaluation of high-frequency ground motion input. In such a case, a COL applicant would confirm that the site-specific, high-frequency ground motion input and the underlying site profile are encompassed by the generic evaluation. When referencing a certified design, a COL applicant may also conduct site-specific SSI analysis that considers incoherency effects to reduce the high-frequency response. In this case, the site-specific, in-structure responses should be enveloped by the responses obtained from the analysis of the CSDRS; further guidance can be found in DSRS Section 3.7.1 II.4.

Methods other than those described above (such as use of random vibration theory, etc.) may also be used for SSI analyses. The acceptability of these methods will be determined on a case-by-case basis.

5. Development of In-Structure Response Spectra. RG 1.122, "Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components," describes methods generally acceptable to the staff for developing the two horizontal and the vertical ISRS (e.g., floor response spectra) from the time history motions resulting from the dynamic analysis of the supporting structure. The topics addressed are:

   A. Square root of the sum of the squares (SRSS) combination of the three ISRS in a given direction (e.g., *x* direction), developed from the output time histories from separate analyses of the three directions (*x*, *y*, *z*) of input motion. SRSS combination is not applicable if the three directions of the input motion are applied simultaneously in a single analysis.

   B. Frequency increments for calculation of spectral accelerations.

   C. Spectrum smoothing and broadening to account for uncertainty.

   The guidance in RG 1.122 is augmented as follows:

   A. The SRSS combination applies to all cases where the three directions of input motion (two horizontal and one vertical) are analyzed separately. There is no longer a distinction made between symmetric and unsymmetric structures.

   B. The 3-Hz frequency increment in the last row of RG 1.122, Table 1, applies up to the highest frequency of interest. The highest frequency of interest typically is the PGA frequency of the design ground response spectrum, which in some cases may significantly exceed 33 Hz.

   C. When a single set of three time histories is used as the input motion to the supporting structure, the ISRS are smoothed and broadened in accordance with the provisions of RG 1.122, to account for uncertainty.

   D. When multiple sets of three time histories, derived from actual earthquake records, are used as the input motion to the supporting structure, the multiple sets of ISRS already account for some of the uncertainty. Therefore, the provisions of RG 1.122, to account for uncertainty, do not strictly apply.

      The use of multiple sets of time histories to generate ISRS is reviewed and accepted on a case-by-case basis. Particularly, the basis for procedures used to account for uncertainties (by variation of parameters) are evaluated.

The same acceptance criteria apply to the ISRS as apply to the design ground response spectrum, reviewed in Subsection II.1.B of DSRS Section 3.7.1. As an example, if the average of the multiple response spectra generated from the multiple design time histories is used to envelop the design ground response spectrum, then the average of the multiple ISRS generated from the multiple analyses (each of which used one of the multiple design time histories) is used in design.

The methods used for direct generation of ISRS are reviewed and accepted on a case-by-case basis.

6. Three Components of Design Ground Motion. RG 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis," describes acceptable methods for combining the responses due to three components of design ground motion, for both the response spectrum method and the time history method. Use of alternate methods is evaluated on a case-by-case basis for acceptability.

   When the three components of design ground motion are applied simultaneously, using a set of three time histories, the statistical independence of the time histories should be demonstrated. See Subsection II.1.B of DSRS Section 3.7.1 for the acceptance criteria to demonstrate statistical independence.

7. Combination of Modal Responses. RG 1.92 describes acceptable methods for combination of modal responses, including consideration of closely spaced modes and high-frequency modes, when the response spectrum method or the modal superposition time history method of analysis is used to determine the dynamic response of damped linear systems. Use of alternate methods is evaluated on a case-by-case basis for acceptability.

8. Interaction of Non-Seismic Category I Structures with Seismic Category I SSCs. All non-seismic Category I structures should be assessed to determine whether their failure under SSE conditions could impair the integrity of seismic Category I SSCs, or result in incapacitating injury to control room occupants. Each non-seismic Category I structure should meet at least one of the following criteria:

   A. The collapse of the non-seismic Category I structure will not cause the non-seismic Category I structure to strike a seismic Category I SSC.

   B. The collapse of the non-seismic Category I structure will not impair the integrity of seismic Category I SSCs, nor result in incapacitating injury to control room occupants.

   C. The non-seismic Category I structure will be analyzed and designed to prevent its failure under SSE conditions.

   The disposition of each non-seismic Category I structure should be formally documented.

For criterion B, it is necessary to provide the technical basis for the determination that collapse of the non-seismic Category I structure is acceptable. This should include a description of any additional loads imposed on the seismic Category I SSCs and the method used to conclude that these loads are not damaging. Also, any protective shields installed to prevent direct impact on seismic Category I SSCs should be described.

For criterion C, it is necessary to demonstrate that there is no physical interaction between the non-seismic Category I structure and all adjacent seismic Category I SSCs. The maximum permissible displacement of the non-seismic Category I structure in any direction is determined by subtracting the maximum calculated displacement of each adjacent seismic Category I SSC in the direction of the non-seismic Category I structure from the minimum as-designed gap, considering construction tolerances. The criterion of no physical interaction needs to be demonstrated for all elevations of the non-seismic Category I structure, taking into consideration the potential for sliding and rocking of the non-seismic Category I structure.

A conservative way to address criterion C is to apply a linear elastic analysis to the non-seismic Category I structure, similar to seismic Category I structures. However, depending on the magnitude of the gap existing between the non-seismic Category I structure and the adjacent seismic Category I SSCs, a limited inelastic response may be permissible for the non-seismic Category I structure, provided the structural integrity of the non-seismic Category I structure can be demonstrated, in determining that there is no physical interaction between the non-seismic Category I structure and all adjacent seismic Category I SSCs. In the assessment, the effect of structure-soil-structure interaction (SSSI) should be accounted for, if significant.

If an inelastic response method is utilized to address criterion C, the demand may be determined using several methods that consider the nonlinear behavior of the structure (e.g., nonlinear static analysis or nonlinear dynamic analysis). If a nonlinear time history analysis is utilized, then the guidance in DSRS Section 3.7.1 II.1.B, Option 2, related to the use of multiple time histories for nonlinear analysis, should be followed. In this case, the acceptance criteria with respect to permissible displacements should be satisfied for each individual time history analysis. The use of inelastic response methods and acceptance criteria is reviewed by the staff on a case-by-case basis.

To ensure an adequate evaluation of the seismic Category I SSCs in a DC application, it is necessary to determine that they are not vulnerable to the collapse of or interaction with adjacent non-seismic Category I structures. Consequently, DC applicants should provide sufficient analysis and design information concerning interaction of the non-seismic Category I structures with seismic Category I SSCs for staff review. In lieu of this, the DC application should describe the analysis and design approach that will be implemented by a COL applicant, and also identify a COL information item requiring that an evaluation be performed and documented to address the interaction of non-seismic Category I structures with seismic Category I SSCs. In addition, associated ITAAC (e.g., check of as-built vs. as-designed gaps; reconciliation of as-built vs. as-designed geometry and material specifications for the non-seismic Category I structures) should be identified.

9. Effects of Parameter Variations on Floor Response Spectra. Consideration should be given in the analysis to the effects on floor response spectra (e.g., peak width) of expected variations of structural properties, damping values, soil properties, and SSI. The acceptance criteria for the consideration of the effects of parameter variations are provided in Subsection II.5 of this DSRS section. In addition, for concrete structures, the effect of potential concrete cracking on the structural stiffness should be specifically addressed in accordance with Subsection II.3.C.iv of this DSRS section.

10. Use of Equivalent Vertical Static Factors. The use of equivalent static load factors to calculate vertical response loads for the seismic design of seismic Category I SSCs, in lieu of the use of a vertical seismic system dynamic analysis, is acceptable only if it can be demonstrated that the SSC is rigid in the vertical direction, or the acceptance criteria in Subsection II.1.B of this DSRS section are satisfied. The criterion for rigidity is that the lowest frequency in the vertical direction is higher than the ZPA frequency of the input ground or in-structure spectrum.

11. Methods Used to Account for Torsional Effects. An acceptable method to account for torsional effects in the seismic analysis of seismic Category I structures is to perform a dynamic analysis that incorporates the torsional degrees of freedom. An acceptable alternative, if properly justified, is the use of static factors to account for torsional accelerations in the seismic design of seismic Category I structures.

    To account for accidental torsion, an additional eccentricity of plus or minus 5 percent of the maximum building dimension should be assumed for both horizontal directions. The magnitude and location of the two eccentricities are determined separately for each floor elevation.

12. Comparison of Responses. If both the time history analysis method and the response spectrum analysis method are used to analyze an SSC, the peak responses obtained from these two methods should be compared to demonstrate approximate equivalency between the two methods.

13. Analysis Procedure for Damping. Either the composite modal damping approach or the modal synthesis technique can be used to account for element-associated damping. Use of composite modal damping for computing the response of systems with nonclassical modes may lead to nonconservative results (Miller, et al., 1985). Therefore, the composite modal damping approach is acceptable provided the composite modal damping is limited to 20 percent. One of the other methods mentioned below is generally applicable if the composite modal damping exceeds 20 percent.

    A. time domain analysis using complex modes/frequencies
    B. frequency domain analysis
    C. direct integration of uncoupled equation of motion

    For the composite modal damping approach, two techniques of determining an equivalent modal damping matrix or composite damping matrix are commonly used. They are based on the use of the mass or stiffness as a weighting function in generating the composite modal damping. The formulations lead to:

$$\bar{\beta}_j = \{\varphi\}^T [\bar{M}] \{\varphi\} \tag{1}$$

$$\beta_j = \frac{\{\varphi\}^T [\bar{K}] \{\varphi\}}{K^*} \tag{2}$$

where

K^* = $\{\varphi\}^T [K] \{\varphi\}$,

[K] = assembled stiffness matrix,

$\bar{\beta}_j$ = equivalent modal damping ratio of the j^{th} mode,

$[\bar{K}]$, $[\bar{M}]$ = the modified stiffness or mass matrix constructed from element matrices formed by the product of the damping ratio for the element and its stiffness or mass matrix, and

$\{\varphi\}$ = j^{th} normalized modal vector.

For models that take SSI into account by the lumped soil spring approach, the method defined by Equation 2 is acceptable. For fixed base models, either Equation 1 or 2 may be used. Other techniques based on modal synthesis have been developed and are particularly useful when more detailed data on the damping characteristics of structural subsystems are available. The modal synthesis analysis procedure consists of (1) extraction of sufficient modes from the structure model, (2) extraction of sufficient modes from the finite element soil model, and (3) performance of a coupled analysis using the modal synthesis technique, which uses the data obtained in steps (1) and (2) with appropriate damping ratios for structure and soil subsystems. This method is based upon satisfaction of displacement compatibility and force equilibrium at the system interfaces and uses subsystem eigenvectors as internal generalized coordinates. This method results in a nonproportional damping matrix for the composite structure, and equations of motion have to be solved by direct integration or by uncoupling them by use of complex eigenvectors.

Other techniques for estimating the equivalent modal damping of an SSI model are reviewed on a case-by-case basis.

14. Determination of Seismic Overturning Moments and Sliding Forces, Structure to Soil Pressures and Frictional Forces for Seismic Category I Structures. To be acceptable, the determination of (1) the design seismic overturning moments and sliding forces, (2) structure to soil pressures beneath the foundation and alongside walls (including potential sliding and separation effects), and (3) soil friction should incorporate the following items:

A. three components of input motion

B. conservative consideration of the simultaneous action of vertical and horizontal seismic effects over the depth of the facility

Additional information on load combinations is provided in DSRS Section 3.8.5.

Technical Rationale

The technical rationale for application of these acceptance criteria to the areas of review addressed by this DSRS section is discussed in the following paragraphs:

1. GDC 2 in 10 CFR Part 50 requires, in the relevant parts, that SSCs important to safety be designed to withstand the effects of natural phenomena such as earthquakes, without loss of capability to perform their intended safety functions. GDC 2 further requires that the design bases reflect appropriate consideration of the most severe natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated.

   DSRS Section 3.7.2 describes acceptable methods for the seismic analysis and modeling of seismic Category I structures and major plant systems to assure that they accurately and/or conservatively represent the behavior of SSCs during postulated seismic events. These criteria include acceptable methods/procedures for performing a suitable dynamic analysis, including the effects of SSI. Additional guidance is included in RGs 1.92 and 1.122. RG 1.92 provides various procedures acceptable to the staff for combining the three-dimensional modal responses for both the response spectrum analysis approach and the time history analysis approach of NPP structures. Additionally, RG 1.122 describes methods acceptable to the staff, as augmented in this DSRS section, for developing three in-structure design response spectra (two horizontal and one vertical) at various floors or other equipment support locations of interest, from the time history motions resulting from the dynamic analysis of the supporting structure. DSRS Section 3.7.2 also describes criteria and/or requirements for considering the interaction of non-seismic Category I structures with seismic Category I SSCs, the treatment of torsional effects, the procedures for considering the effects of damping, and the determination of seismic overturning moments and sliding forces.

   Meeting these criteria provides assurance that seismic Category I systems will be adequately designed to withstand the effects of earthquakes without loss of capability to perform their safety functions.

2. Appendix S to 10 CFR Part 50 is applicable to applications for a DC or COL pursuant to 10 CFR Part 52 or a CP or OL pursuant to 10 CFR Part 50 on or after January 10, 1997. For SSE ground motions, 10 CFR Part 50, Appendix S, requires that certain SSCs will remain functional and within applicable stress, strain, and deformation limits. The required safety functions of these SSCs must be assured during and after the vibratory ground motion associated with the SSE ground motion through design, testing, or

qualification methods. The evaluation must take into account SSI effects and the expected duration of the vibratory motion. If the OBE is set at one-third or less of the SSE, an explicit response or design analysis is not required. If the OBE is set at a value greater than one-third of the SSE, an analysis and design must be performed to demonstrate that, when subjected to the effects of the OBE in combination with normal operating loads, all SSCs of the nuclear power plant necessary for continued operation without undue risk to the health and safety of the public remain functional and within applicable stress, strain, and deformation limits. Appendix S also requires that the horizontal component of the SSE ground motion in the free field at the foundation level of the structures must be an appropriate response spectrum with a PGA of at least 0.1g.

DSRS Section 3.7.2 describes acceptable analytical methods that are used to determine the seismic response of structures and systems in terms of stresses, strains, and deformations. These responses are combined with the structural responses from other loads in accordance with the criteria in DSRS Sections 3.8.2, 3.8.4, and 3.8.5. The criteria in DSRS Section 3.7.2 ensure that the effects of the three components of design ground motion and the effects of SSI are appropriately included in the evaluation. In addition, the use of these criteria allows the SSI analysis to calculate the floor response spectra for use in qualification of equipment.

Meeting these criteria provides assurance that appropriate methods will be used to determine the structural response of systems under the SSE and OBE (if applicable), which will ensure that they will remain functional within applicable acceptance limits.

III. REVIEW PROCEDURES

These review procedures are based on the identified DSRS acceptance criteria. For deviations from these acceptance criteria, the staff should review the applicant's evaluation of how the proposed alternatives provide an acceptable method of complying with the relevant NRC requirements identified in Subsection II of this DSRS section.

1. Selected Programs and Guidance—In accordance with the guidance in NUREG–0800, "Introduction – Part 2: Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: Light-Water Small Modular Reactor Edition" (NUREG-0800, Intro Part 2), as applied to this DSRS Section, the staff will review the information proposed by the applicant to evaluate whether it meets the acceptance criteria described in Subsection II of this DSRS. As noted in NUREG-0800, Intro Part 2, the NRC requirements that must be met by an SSC do not change under the small modular reactor (SMR) framework. Using the graded approach described in NUREG-0800, Intro Part 2, the NRC staff may determine that, for certain SSCs, the applicant's basis for compliance with other selected NRC requirements may help demonstrate satisfaction of the applicable acceptance criteria for that SSC in lieu of detailed independent analyses. The design-basis capabilities of specific SSCs would be verified, where applicable, as part of completing the applicable ITAAC. The use of the selected programs to augment or replace traditional review procedures is shown in Figure 1 of NUREG-0800, Intro Part 2. Examples of such programs that may be relevant to the graded approach for these SSCs include:

    - 10 CFR Part 50, Appendix A, GDC, Overall Requirements, Criteria 1–5

- 10 CFR Part 50, Appendix B, Quality Assurance (QA) Program
- 10 CFR 50.49, Environmental Qualification of Electrical Equipment (EQ) Program
- 10 CFR 50.55a, Code Design, Inservice Inspection, and Inservice Testing (ISI/IST) Programs
- 10 CFR 50.65, Maintenance Rule requirements
- Reliability Assurance Program (RAP)
- 10 CFR 50.36, "Technical Specifications"
- Availability Controls for SSCs Subject to Regulatory Treatment of Nonsafety Systems (RTNSS)
- Initial Test Program (ITP)
- Inspections, Tests, Analyses, and Acceptance Criteria (ITAAC)

This list of examples is not intended to be all inclusive. It is the responsibility of the technical reviewers to determine whether the information in the application, including the degree to which the applicant seeks to rely on such selected programs and guidance, demonstrates that all acceptance criteria have been met to support the safety finding for a particular SSC.

2. In accordance with 10 CFR 52.47(a)(8), (21), and (22), and 10 CFR 52.79(a)(17), (20), and (37), for DC or COL applications submitted under 10 CFR Part 52, the applicant is required to (1) address the proposed technical resolution of unresolved safety issues and medium- and high-priority generic safety issues which are identified in the version of NUREG-0933, "Resolution of Generic Safety Issues," current on the date up to 6 months before the docket date of the application and which are technically relevant to the design, (2) demonstrate how the operating experience insights have been incorporated into the plant design, and (3) provide information necessary to demonstrate compliance with any technically relevant portions of the Three Mile Island requirements set forth in 10 CFR 50.34(f), except paragraphs (f)(1)(xii), (f)(2)(ix), and (f)(3)(v), for a DC application, and except paragraphs (f)(1)(xii), (f)(2)(ix), (f)(2)(xxv), and (f)(3)(v), for a COL application. These cross-cutting review areas should be addressed by the reviewer for each technical subsection and relevant conclusions documented in the corresponding safety evaluation report (SER) section.

3. <u>Seismic Analysis Methods</u>. For all seismic Category I SSCs, the applicable methods of seismic analysis (response spectra, time history, and equivalent static load) are reviewed to confirm that the techniques employed are in accordance with the acceptance criteria as given in Subsection II.1 of this DSRS section. If empirical methods or tests are used in lieu of analysis for any seismic Category I structure,

these are evaluated to determine whether or not the assumptions are conservative and whether the test procedure adequately models the seismic response.

4. Natural Frequencies and Response Loads. The summary of natural frequencies and response loads is reviewed to confirm that the acceptance criteria in Subsection II.2 of this DSRS section are met.

5. Procedures Used for Analytical Modeling. The procedures used for modeling of seismic systems are reviewed to determine whether the three-dimensional characteristics of structures are properly modeled in accordance with the acceptance criteria of Subsection II.3 of this DSRS section and whether all significant degrees of freedom have been incorporated in the models. The criteria for decoupling of a structure, equipment, or component and analyzing it separately as a subsystem are reviewed for conformance with the acceptance criteria given in Subsection II.3 of this DSRS section.

6. Soil-Structure Interaction. The methods of SSI analysis used are examined to determine that the techniques employed are in accordance with the acceptance criteria as given in Subsection II.4 of this DSRS section. Typical mathematical models for SSI analysis are reviewed to ensure the adequacy of the representation of the soil-structure system in accordance with Subsection II.4 of this DSRS section. In addition, the methods used to assess the effects of adjacent structures on structural response in SSI analysis are reviewed to establish their acceptability.

7. Development of In-Structure Response Spectra. Procedures for developing the ISRS are reviewed to verify that they are in accordance with the acceptance criteria specified in Subsection II.5 of this DSRS section. If a direct generation method of analysis is used to develop the ISRS, its conservatism compared to that of a time history approach is reviewed.

8. Three Components of Design Ground Motion. The procedures by which the three components of design ground motion are considered in determining the seismic response of SSCs are reviewed to confirm that the acceptance criteria of Subsection II.6 of this DSRS section are met.

9. Combination of Modal Responses. The procedures for combining modal responses are reviewed to confirm that the acceptance criteria of Subsection II.7 of this DSRS section are met.

10. Interaction of Non-Seismic Category I Structures with Seismic Category I SSCs. The design and analysis criteria for interaction of non-seismic Category I structures with seismic Category I SSCs are reviewed to confirm that the acceptance criteria of Subsection II.8 of this DSRS section are met.

11. Effects of Parameter Variations on Floor Response Spectra. The seismic system analysis is reviewed to determine whether the analysis considered the effects of expected variations of structural properties, damping values, soil properties, and SSI on floor response spectra (e.g., peak width) and to confirm that the acceptance criteria of Subsection II.9 of this DSRS section are met. Among the various structural parameters

analyzed, the effect of potential concrete cracking on structural stiffness should be addressed.

12. <u>Use of Equivalent Vertical Static Factors</u>. Use of constant static factors as response loads in the vertical direction for the seismic design of any seismic Category I SSC, in lieu of a detailed dynamic method, is reviewed to confirm that the acceptance criteria of Subsection II.10 of this DSRS section are met.

13. <u>Methods Used to Account for Torsional Effects</u>. The methods of seismic analysis are reviewed to determine that the torsional effects of vibration are incorporated, in accordance with the acceptance criteria of Subsection II.11 of this DSRS section. The staff will review the applicant's justification for using any approximate method to account for torsional effects to ensure that the method results in a conservative design.

14. <u>Comparison of Responses</u>. Where applicable, the responses obtained from both time history and response spectrum methods at selected points in major seismic Category I structures are compared to judge the accuracy of the analyses conducted. The applicant should explain any significant discrepancies in the results of the two methods.

15. <u>Analysis Procedure for Damping</u>. The analysis procedure to account for differences in damping in different elements of the system structural model is reviewed to determine that it is in accordance with the acceptance criteria of Subsection II.13 of this DSRS section.

16. <u>Determination of Seismic Overturning Moments and Sliding Forces, Structure to Soil Pressures and Frictional Forces for Seismic Category I Structures</u>. The analysis methods to calculate (1) seismic overturning moments and sliding forces, (2) structure to soil pressures beneath the foundation and alongside walls, and (3) soil friction are reviewed to determine compliance with the acceptance criteria of Subsection II.14 of this DSRS section.

17. <u>Design Certification and Combined License Reviews</u>. For review of a DC application, the reviewer should follow the above procedures to verify that the design, including requirements and restrictions (e.g., interface requirements and site parameters), set forth in the FSAR meets the acceptance criteria. DCs have referred to the FSAR as the DCD. The reviewer should also consider the appropriateness of identified COL action items. The reviewer may identify additional COL action items; however, to ensure that these COL action items are addressed during a COL application, they should be added to the DC FSAR.

    For review of a COL application, the scope of the review is dependent on whether the COL applicant references a DC, an ESP, or other NRC approvals (e.g., manufacturing license, site suitability report, or topical report).

    For review of both DC and COL applications, SRP Section 14.3 should be followed for the review of ITAAC. The review of ITAAC cannot be completed until after the completion of this section.

IV. EVALUATION FINDINGS

(Combined for DSRS Sections 3.7.2 and 3.7.3)

The reviewer verifies that the applicant has provided sufficient information and that the review and calculations (if applicable) support conclusions of the following type to be included in the staff's SER. The reviewer also states the bases for those conclusions.

The staff concludes that the plant design is acceptable and meets the requirements of 10 CFR Part 50, GDC 2. This conclusion is based on the following: The applicant has met the requirements of GDC 2 and 10 CFR Part 50, Appendix S, with respect to the capability of the structures to withstand the effects of earthquakes so that the design reflects:

1. appropriate consideration of the most severe earthquake recorded for the site with an appropriate margin (GDC 2), and appropriate consideration of the OBE and SSE (10 CFR Part 50, Appendix S)

2. appropriate combination of the effects of normal and accident conditions with the effect of the natural phenomena (GDC 2 and 10 CFR Part 50, Appendix S)

3. the importance of the safety functions to be performed (GDC 2)

4. the use of a suitable dynamic analysis or a suitable qualification test to demonstrate that SSCs can withstand the seismic and other concurrent loads, except where it can be demonstrated that the use of an equivalent static load method provides adequate consideration (10 CFR Part 50, Appendix S)

   The applicant has met the requirements of item 1 listed above by use of the acceptable seismic design parameters per DSRS Section 3.7.1. The combination of earthquake resultant loads with those resulting from normal and accident conditions in the design of seismic Category I structures as specified in DSRS Sections 3.8.4, and 3.8.5 will result in conformance with item 2 listed above.

   The scope of review of the seismic system and subsystem analysis for the plant included the seismic analysis methods for all seismic Category I SSCs. The review scope included procedures for modeling, seismic SSI, development of floor response spectra, inclusion of torsional effects, seismic analysis of seismic Category I concrete dams, evaluation of seismic Category I structure overturning, and determination of composite damping. The review included design criteria and procedures for evaluation of the interaction of non-seismic Category I structures with seismic Category I structures and the effects of parameter variations on floor response spectra.

   The review also included criteria and seismic analysis procedures for seismic Category I buried piping and aboveground seismic Category I tanks.

   The system and subsystem analyses were performed by the applicant on an elastic and linear basis. Time history methods form the bases for the analyses of all major seismic Category I SSCs. The methods used in combining modal responses are in conformance with the regulatory positions in RG 1.92. Alternate methods have been evaluated and found to be acceptable. Floor spectra inputs for design and test verifications of SSCs were generated from the time history method in conformance with the position of RG 1.122, as augmented in DSRS Section 3.7.2. A vertical seismic system dynamic analysis is employed for all SSCs where analyses show significant structural amplification in the vertical direction. Torsional effects and stability against overturning have been appropriately considered.

A coupled structure and soil model was used to evaluate SSI effects upon seismic responses. Appropriate nonlinear stress-strain and damping relationships for the soil were appropriately considered in the analysis. The staff concludes (1) that the applicant's seismic structural analysis procedures and criteria delineated above provide an acceptable basis for the seismic design and (2) that the seismic design is in conformance with the applicable NRC regulations.

For DC and COL reviews, the findings will also summarize the staff's evaluation of requirements and restrictions (e.g., interface requirements and site parameters) and COL action items relevant to this DSRS section.

In addition, to the extent that the review is not discussed in other SER sections, the findings will summarize the staff's evaluation of the ITAAC, including design acceptance criteria, as applicable.

V. IMPLEMENTATION

The regulations in 10 CFR 52.17(a)(1)(xii), 10 CFR 52.47(a)(9), and 10 CFR 52.79(a)(41) establish requirements for applications for ESPs, DCs, and COLs, respectively. These regulations require the application to include an evaluation of the site (ESP), standard plant design (DC), or facility (COL) against the SRP revision in effect 6 months before the docket date of the application. While the SRP provides generic guidance, the staff developed the SRP guidance based on the staff's experience in reviewing applications for construction permits and operating licenses for large light-water nuclear power reactors. The proposed SMR designs, however, differ significantly from large light-water nuclear power plant designs.

In view of the differences between the designs of SMRs and the designs of large light-water power reactors, the Commission issued Staff Requirements Memorandum (SRM)-COMGBJ-10-0004/COMGEA-10-0001, "Use of Risk Insights To Enhance Safety Focus of Small Modular Reactor Reviews," dated August 31, 2010. In the SRM, the Commission directed the staff to develop risk-informed licensing review plans for each of the SMR design reviews, including plans for the associated preapplication activities. Accordingly, the staff has developed the content of the DSRS as an alternative method for evaluating a NuScale-specific application submitted pursuant to 10 CFR Part 52, and the staff has determined that each application may address the DSRS in lieu of addressing the SRP, with specified exceptions. These exceptions include particular review areas in which the DSRS directs reviewers to consult the SRP and others in which the SRP is used for the review. If an applicant chooses to address the DSRS, the application should identify and describe all differences between the design features (DC and COL applications only), analytical techniques, and procedural measures proposed in an application and the guidance of the applicable DSRS section (or SRP section, as specified in the DSRS), and discuss how the proposed alternative provides an acceptable method of complying with the regulations that underlie the DSRS acceptance criteria.

The staff has accepted the content of the DSRS as an alternative method for evaluating whether an application complies with NRC regulations for NuScale SMR applications, provided that the application does not deviate significantly from the design and siting assumptions made by the NRC staff while preparing the DSRS. If the design or siting assumptions in a NuScale application deviate significantly from the design and siting assumptions the staff used in preparing the DSRS, the staff will use the more general guidance in the SRP, as specified in 10 CFR 52.17(a)(1)(xii), 10 CFR 52.47(a)(9), or 10 CFR 52.79(a)(41), depending on the type of application. Alternatively, the staff may supplement the DSRS section by adding appropriate criteria to address new design or siting assumptions.

VI. REFERENCES

1. *U.S. Code of Federal Regulations*, "General Design Criteria for Nuclear Power Plants," Appendix A, Part 50, Chapter I, Title 10, "Energy."

2. 10 CFR Part 50, Appendix A, General Design Criterion 2, "Design Bases for Protection Against Natural Phenomena."

3. *U.S. Code of Federal Regulations*, "Earthquake Engineering Criteria for Nuclear Power Plants," Appendix S, Part 50, Chapter I, Title 10, "Energy."

4. *U.S. Code of Federal Regulations*, "Licenses, Certifications, and Approvals for Nuclear Power Plants," Part 52, Chapter I, Title 10, "Energy."

5. American Society of Civil Engineers, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities." ASCE/SEI 43-05, 2005.

6. Miller, C.A., C.J. Costantino, and A.J. Philippacopoulos, "High Soil-Structure Damping Combined with Low Structural Damping," *7th Structural Mechanics in Reactor Technology (SMiRT) Paper K 10/10*, Chicago, IL, 1985.

7. U.S. Nuclear Regulatory Commission, "Proceedings of the Workshop on Soil-Structure Interaction," NUREG/CP-0054, Bethesda, MD, June 16–18, 1986, ADAMS Accession No. ML13214A087.

8. U.S. Nuclear Regulatory Commission, "Recommended Revisions to Nuclear Regulatory Commission Seismic Design Criteria," NUREG/CR-1161, May 1980.

9. U.S. Nuclear Regulatory Commission, "Design Response Spectra for Seismic Design of Nuclear Power Plants," RG 1.60, ADAMS Accession No. ML13210A432.

10. U.S. Nuclear Regulatory Commission, "Damping Values for Seismic Design of Nuclear Power Plants," RG 1.61.

11. U.S. Nuclear Regulatory Commission, "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants," RG 1.70, ADAMS Accession No. ML011340072.

12. U.S. Nuclear Regulatory Commission, “Combining Modal Responses and Spatial Components in Seismic Response Analysis,” RG 1.92, ADAMS Accession No. ML053250475.

13. U.S. Nuclear Regulatory Commission, “Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components.” RG 1.122, ADAMS Accession No. ML003739367.

14. U.S. Nuclear Regulatory Commission, “Site Investigations for Foundations of Nuclear Power Plants,” RG 1.132, ADAMS Accession No. ML032790474.

15. U.S. Nuclear Regulatory Commission, “Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants,” RG 1.138, ADAMS Accession No. ML14289A600.

16. U.S. Nuclear Regulatory Commission, “Combined License Applications for Nuclear Power Plants (LWR Edition),” RG 1.206.

17. ASCE/SEI 43-05, “Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities.” American Society of Civil Engineers, 2005.

18. U.S. Nuclear Regulatory Commission, “Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications,” DC/COL-ISG-01, June 12, 2009, ADAMS Accession No. ML081400293.

19. U.S. Nuclear Regulatory Commission, “Interim Staff Guidance on Ensuring Hazard-Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses,” DC/COL-ISG-017, April 15, 2010, ADAMS Accession No. ML100570203.

20. U.S. Nuclear Regulatory Commission, “Interim Staff Guidance on Implementation of a Probabilistic Risk Assessment-Based Seismic Margin Analysis for New Reactors,” DC/COL-ISG-020, March 15, 2010, ADAMS Accession No. ML100491233.

APPENDIX A: AUDIT GUIDELINES FOR DSRS SECTION 3.7.1 through 3.7.4 SEISMIC DESIGN REVIEW

1. Introduction

This appendix provides guidelines for implementation of seismic design audits. The audit process is an important element of the staff's review activities. It provides an opportunity to examine pertinent technical information that supports, but is not included in, a license or certification application. It also serves as a forum for detailed face-to-face discussion with the applicant about this supporting technical information. The audit allows the staff to confirm the acceptability of the application information.

2. Audit Arrangements

Arrangements for the audit are made by the responsible licensing project manager (LPM). The audit agenda, including specific areas of interest, is prepared by the U.S. Nuclear Regulatory Commission (NRC) lead technical reviewer. The audit agenda is forwarded to the applicant by the LPM at least 2 weeks prior to the start of the audit. The LPM should notify the appropriate regional office personnel, as well as any intervening parties, if applicable, about the forthcoming audit.

3. Audit Team

The audit team consists of the LPM, the NRC lead technical reviewer, and a number of technical experts, composed of NRC staff and/or NRC contractor staff. The LPM acts as the contact between the NRC audit team and the applicant. The NRC lead technical reviewer is responsible for the resolution of all technical issues and will determine the number of team members and the areas of expertise needed to accomplish the audit objectives.

4. Number and Duration of Audits

In general, two audits should be planned. The first audit is conducted after the staff's review of the applicant's initial responses to the staff's requests for additional information (RAIs). The second audit is conducted near the end of the review process. At the end of the second audit, the remaining unresolved technical issues should be clearly defined by the staff and clearly understood by the applicant.

Usually, 4 working days should be planned for each audit, to allow sufficient time to complete the audit scope.

5. Audit Objectives

(1) Obtain and review additional pertinent technical information that is not documented in the application (e.g., Sections 3.7.1 through 3.7.3 of the Design Control Document).

(2) Perform review of the applicant's seismic analyses and calculations.

(3) Discuss the applicant's responses to the unresolved RAIs.

(4) Obtain technical information (structural models, design site parameters, structural drawings, input ground motion time history, etc.) from the applicant, for use by the staff in performing its independent seismic analyses as appropriate. (first audit)

(5) Resolve any discrepancies between the staff's independent analysis results and the results of the applicant's analyses, after the staff's analyses are completed. (second audit)

(6) Identify and document any new outstanding issues (new RAIs) resulting from (1) through (5) above, including the identification of information that must be included in the application to support the staff's safety finding.

6. Conduct of the Audit

(1) Entrance Meeting

An entrance meeting is conducted at the beginning of the audit. The LPM will briefly summarize the purpose of the audit and introduce the NRC audit team members to the applicant. The NRC lead technical reviewer will discuss the purpose and scope of the audit in greater detail. The applicant will introduce its technical team that is available to support the staff during the audit. At its own discretion or as requested by the staff, the applicant may present an overview of its technical approach to seismic analysis of the seismic Category I plant structures, including a description of assumptions, analysis methods, computer codes used, modeling techniques, and analysis results. The applicant should identify and discuss any changes in the technical approach from those identified and discussed in its application. The time allotted for the entrance meeting will vary from audit to audit, but should be limited to no more than 3 hours. (The LPM determines whether the entrance meeting is a public meeting.)

(2) Audit Activities

There is no fixed format for conduct of the audit activities. The audit team may work as a single group, a number of smaller groups, or individually, at the direction of the NRC lead technical reviewer. Typically, at the end of each workday, the NRC lead technical reviewer compiles a summary of the audit team's activities and findings, assesses progress toward completion of the audit scope, and informs the applicant of the audit status. Any new technical issues and/or specific needs for additional information are communicated to the applicant.

Informal discussions between audit team members and the applicant's technical staff should be limited to exchanges of information. All important audit findings and conclusions should be communicated to the applicant's responsible manager by the NRC lead technical reviewer.

The audit team's activities should primarily focus on (a) review of pertinent technical information that the applicant referenced in its RAI responses, (b) confirmation, through review of formal calculations and design/analysis reports, that the applicant's technical approach to seismic analysis of the seismic Category I plant structures, as identified and discussed in the application, has been appropriately implemented, and (c) as applicable, discussions related to the staff's independent confirmatory analyses.

Topics of special interest include:

- development of the ground motion time histories to match the design-basis ground response spectrum

- modeling of soil properties

- modal properties of the structural models; confirmation of adequate refinement relative to the frequency content of the design-basis ground response spectrum

- methodologies employed (computer codes, computer models) to conduct seismic analysis, including soil-structure interaction effects

- in-structure response spectra

(3) Exit Meeting

An exit meeting is conducted at the conclusion of the audit, to discuss and summarize the audit findings, the unresolved RAIs, any new outstanding issues identified, and the applicant's schedule for responding to the audit issues identified. One hour is allotted for the exit meeting. (The LPM determines whether the exit meeting is a public meeting.)

7. Audit Report

The NRC lead technical reviewer will prepare a summary of progress toward resolution of technical issues and a description of any new outstanding technical issues that emerged during the audit. The LPM is responsible for preparation of an audit summary report.

8. Post-audit Communications

Review of the applicant's responses to the issues identified during the audit may necessitate additional meeting(s) or conference call(s) between the staff and the applicant, to obtain clarification of the responses.

9. Input to the Safety Evaluation Report

The audits are an integral part of the staff's review process. The audit results, the resolution of the RAIs and open items, and appropriate consideration of other safety aspects constitute the major basis for the staff's preparation of the SER.