U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

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:

For all seismic Category I structures, systems, and components (SSCs), the applicable seismic analysis methods (response spectrum analysis method, time history analysis method or equivalent static load analysis method) are reviewed. The manner in which the dynamic system analysis is performed, including the modeling of foundation torsion and overall building rocking and translation is reviewed. The modeling of soil-structure interaction (SSI) effects is reviewed. The method chosen for the determination of significant modes and an adequate number of discrete mass degrees of freedom is reviewed. The manner in which consideration is given in the seismic analysis to maximum relative displacements between supports is reviewed. In addition, other significant effects that are accounted for in the seismic analysis such as hydrodynamic effects and nonlinear analysis methods and responses are reviewed. 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 Standard Review Plan (SRP) criteria generally deal with linear elastic analysis, coupled with allowable stresses near 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 criteria and procedures used in modeling for the seismic system analyses (including structural material properties, modeling of member stiffness, modeling of mass [structural masses, live loads, floor loads, and equipment loads], modeling of damping, modeling of hydrodynamic effects, etc.) are reviewed. The criteria and bases for determining whether a structure is analyzed as part of a structural system analysis or independently as a subsystem are also reviewed. In addition, the method used to address floor and wall flexibility in the structural modeling is reviewed.

4. Soil-Structure Interaction. The earthquake ground motion response spectra (GMRS) are defined in the "free-field," i.e., without the presence of structures, at the ground surface. For sites with soil layers near the surface that will be completely excavated to expose competent material, the GMRS are specified on an outcrop or a hypothetical outcrop that will exist after excavation. Motions at this hypothetical outcrop should be developed as a free surface motion, not as an in-column motion. Competent material is defined as in-situ material having a minimum shear wave velocity of 1,000 feet/second (fps). Because of the deformability of the supporting media (rock or soil), the resulting motions at the foundation mat will differ from the corresponding free-field motions. This difference between the foundation mat motion and the free-field motion is known as the SSI effect.

   As applicable, the modeling methods (including technical bases) used in the seismic system analysis to account for SSI are reviewed. 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 soil-structure model. All SSI analyses must recognize the uncertainties prevalent throughout the phenomenon, including:

   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 uniformity in the soil profile, which is usually assumed to be uniformly layered in all horizontal directions.

F. Effects of the flexibility of soil/rock.

G. Effects of the flexibility of basemat.

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

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

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 are reviewed. 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 earthquake 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 earthquake 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 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 (e.g., floor response spectra) are reviewed. There are several methods for generating in-structure response spectra. 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 in-structure response spectra. The basis and justification for the use of either of the above methods are reviewed.

6. Three Components of Earthquake Motion. The staff reviews the procedures by which the three components of earthquake motion (time history or response spectra) are considered in determining the seismic response of all seismic Category I SSCs. If three artificial 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 contribution to the total response due to the effects of high frequency modes (i.e., modes with natural frequencies greater than the frequency at which the spectral acceleration converges to approximately the zero period frequency, ZPA) is reviewed, to ensure that the total response closely simulates the behavior of the SSC during a seismic event. For the case of the Regulatory Guide (RG) 1.60 response spectrum, ZPA is about 33 Hz. 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-Category I Structures with Category I SSCs. The design criteria to account for the seismic motion of non-Category I structures (or portions thereof) in the seismic design of Category I structures (or portions thereof) are reviewed. The seismic design of structures whose continued function is not required but whose failure could adversely impact the safety function of a Category I SSC, or result in incapacitating injury to control room occupants, is reviewed. Any special design features employed to protect Category I SSCs from the structural failure of non-Category I structures, due to seismic effects, are reviewed.

9. Effects of Parameter Variations on Floor Responses. 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 are reviewed.

10. Use of Equivalent Vertical Static Factors. Where applicable, 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, is reviewed.

11. Methods Used to Account for Torsional Effects. The method employed to consider torsional effects in the seismic analysis of 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 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 comparison of seismic responses for major Category I structures using modal response spectrum and time history approaches is reviewed.

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 for Seismic Category I Structures. The description of the method and procedure used to determine design seismic overturning moments and sliding forces for all seismic Category I structures is reviewed.

15. Inspection, Test, Analysis, and Acceptance Criteria (ITAAC). For design certification (DC) and combined license (COL) reviews, the staff reviews the applicant's proposed ITAAC associated with the SSCs (if any are identified related to this SRP section) in accordance with 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 SRP 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 will also address COL action items and requirements and restrictions (e.g., interface requirements and site parameters).

    For a COL application referencing a DC, a COL applicant must address COL action items (referred to as COL license information in certain DCs) included in the referenced DC. Additionally, a 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 on-site 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 SRP section for general guidelines on conducting audits.

Review Interfaces:

Other SRP sections interface with this section as follows:

1. Review of geological and seismological information to establish the free-field earthquake ground motion 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 on-site soil media and soil properties are reviewed under SRP Section 2.5.4.

3. The design earthquake ground motion (response spectra and time histories) is reviewed under SRP Section 3.7.1.

4. Seismic subsystem analysis is reviewed under SRP 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 SRP Sections 3.8.1 through 3.8.5.

The specific acceptance criteria and review procedures are contained in the referenced SRP sections.

The review of the design earthquake ground motion (safe shutdown earthquake (SSE); Operating Basis Earthquake (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. Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, General Design Criterion (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. 10 CFR Part 100, Subpart A, which is applicable to power reactor site applications before January 10, 1997, refers to Appendix A of this part for seismic criteria. 10 CFR Part 100, Appendix A indicates that the SSE and the OBE shall be considered in the design of safety-related SSCs. 10 CFR Part 100, Appendix A further states that the design used to ensure that the required safety functions are maintained during and after the vibratory ground motion associated with the SSE shall involve the use of either 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 conservatism.

   10 CFR Part 100,Subpart B which is applicable to power reactor site applications on or after January 10, 1997, refers to 10 CFR 100.23 of this part for seismic criteria. Section 100.23 describes the criteria and nature of investigations required to obtain the geologic and seismic data necessary to determine the suitability of the proposed site and the plant design bases. 10 CFR 100.23 also indicates that applications to engineering design are contained in 10 CFR Part 50, Appendix S.

3. 10 CFR Part 50, Appendix S is applicable to applications for a DC or COL to 10 CFR Part 52 or a construction permit (CP) or operating license (OL) pursuant to 10 CFR Part 50 on or after January 10, 1997. For SSE ground motions, SSCs will remain functional and within applicable stress, strain, and deformation limits. The required safety functions of SSCs must be assured during and after the vibratory 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 the applicable stress, strain, and deformation limits are satisfied. 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 of at least 0.1g.

4. 10 CFR 52.47(b)(1), which 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 plant that incorporates the DC is built and will operate in accordance with the DC, the provisions of the Atomic Energy Act (AEA), and the U.S. Nuclear Regulatory Commission (NRC) regulations;.

5. 10 CFR 52.80(a), which 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 combined license, the provisions of the AEA, and the NRC regulations.

SRP Acceptance Criteria

Specific SRP acceptance criteria acceptable to meet the relevant requirements of the NRC regulations identified above are as follows for the review described in this SRP section. The SRP is not a substitute for the NRC regulations, and compliance with it is not required. However, an applicant is required to identify differences between the design features, analytical techniques, and procedural measures proposed for its facility and the SRP acceptance criteria and evaluate how the proposed alternatives to the SRP acceptance criteria provide acceptable methods of compliance with the NRC regulations.

1. Seismic Analysis Methods. 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 SRP acceptance criteria primarily address linear elastic analysis coupled with allowable stresses near elastic limits of the structures. However, for certain special cases (e.g., 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 Category 1 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), accounting 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 earthquake 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 (2 horizontal and vertical), all modes with frequencies less than the ZPA (or PGA) frequency of the corresponding 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 (2) 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 (3) 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 $\geq$ ZPA [or PGA] frequency) should be included in the total dynamic solution using the guidance and methods described in RG 1.92, Regulatory Positions C.1.4 and C.1.5.

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.

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, modal and total responses for the Category I structures, including the containment structure, or a summary of the total responses if the method of direct integration is used.

B. The calculated time histories (two horizontal and one vertical), or other parameters of motion, or response spectra (two horizontal and one vertical) used in design, 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, including 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 are used in 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. Category I structures that are considered in conjunction with the foundation and its supporting media are defined as "seismic systems." Other 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:

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

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

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 $0.8 \geq R_f \geq 1.25$.

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: lumped-mass stick model and 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.

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 I structures, the acceptance criteria given in Subsection II.1.a.iv of this SRP section are acceptable.

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 consider 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 in-structure response spectra 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 justification can be provided that 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., in-structure response spectra (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 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 for seismic Category I structures is provided in the acceptance criteria for design and analysis procedures presented in SRP Sections 3.8.1 and 3.8.3 through 3.8.5.

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

For a generic design, where the design-basis in-structure response spectra 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 Certified Seismic Design Response Spectra (CSDRS), the cracked concrete properties and the associated SSE damping values in Table 1 of RG 1.61, can be used. If a CSDRS is associated with a single site condition, such as the hard-rock high-frequency (HRHF) spectra for a specific site, then the use of uncracked concrete properties with OBE damping values in Table 2 of RG 1.61 are acceptable to develop ISRS.

An acceptable approach for existing structures or 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 would be re-run. 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 fall above the amplified portion of the input design response spectra, then the analysis need 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, 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, 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. Soil-Structure Interaction. A complete SSI analysis should properly account for all effects due to kinematic and inertial interaction 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.

B. The design earthquake ground motions used as input to the SSI analyses should be consistent with the design response spectra as defined in SRP Section 3.7.1.

It is noted that there is enough confidence in the current methods used to perform the SSI analysis to capture the basic phenomenon and provide adequate design information; however, the confidence in the ability to implement these methodologies is uncertain. Therefore, in order to ensure proper implementation, the following considerations should be addressed in performing SSI analysis:

A. Perform sensitivity studies to identify important parameters (e.g., potential foundation uplift, separation and sliding of soil from sidewalls, non-symmetry of embedment, location of boundaries) 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; and

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 SRP section.

For sites where SSI effects are considered insignificant and fixed base analyses of structures are performed, bases and justification for not performing SSI analyses are reviewed on a case-by-case basis. If the SSI analysis is not required, the input motion at the base of the structures will be the design motion reviewed in SRP Section 3.7.1.

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 SRP Section 3.8.5 II.4.D uplift evaluations), the effect of the foundation uplift should be evaluated. 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 non-symmetric 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 non-symmetric 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 assessed, and if found important, then it should be accounted for in the seismic design, which is reviewed on a case-by-case basis.

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

A. Modeling of Structure. The acceptance criteria given under subsection II.3 of this SRP section are applicable.

B. Modeling of Supporting Soil. The effect of embedment of structure, ground-water effects, and the layering effect of soil should be accounted for. For the half-space modeling of the soil media, the lumped parameter (soil spring) method and 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.

For structures founded on materials having a shear wave velocity of 8,000 feet per second or higher, under the entire surface of the foundation, a fixed base assumption is acceptable.

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. 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. If the design earthquake ground motion is defined from generic response spectral shapes (e.g, RG 1.60 or NUREG-0098), the location of the ground motion should be consistent with the properties of the soil profile. For profiles consisting of competent soil or rock, with relatively uniform variation of properties with depth, the ground motion should be located at the soil surface at the top of the finished grade. For profiles consisting of one or more soft and/or thin soil layers overlaying competent material, the ground motion should be located at an outcrop (real or hypothetical) at the top of the competent material in the vicinity of the site.

ii. If the design earthquake ground motion is defined from site-specific evaluations of uniform hazard spectra, the location of the ground motion should be at the ground surface in the free-field. In developing the ground motion at the surface, the potential effects of soft soil layers need to be considered. For sites with soil layers near the surface that will be completely excavated to expose competent material, the ground motion response spectra are specified on an outcrop or a hypothetical outcrop that will exist after excavation. Motions at this hypothetical outcrop should be developed as a free surface motion, not as an in-column motion. Competent material is defined as in-situ material having a minimum shear wave velocity of 1,000 feet/second (fps).

iii. When the guidance for SSI analysis presented above is not completely implemented, the spectral amplitude of the acceleration response spectra (horizontal component of motion) in the free field at the foundation depth shall be not less than 60 percent of the corresponding design response spectra at the finished grade in the free field. When the variation in soil properties are considered (as required by the “Specific Guidelines for SSI Analysis” below), the 60 percent limitation may be satisfied using an envelope of the three spectra corresponding to the three soil properties.

If the accompanying rotational components of the input motion are ignored, no reduction is permitted in the horizontal component at the foundation level.

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 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, or

- 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).

- Superposition of horizontal and vertical response 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 shall be consistent with the geotechnical information reviewed in SRP Section 2.5.4.

- For a COL application referencing a standard plant design, where the site-specific GMRS fall below the standard plant CSDRS, the SSI evaluations are addressed in the standard plant design. 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 so as 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 best estimate (BE) profile, a lower bound (LB) and an upper bound (UB) profile in the evaluation of SSI effects. 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.

  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 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 +/- one sigma values. A sufficient number of site response calculations need to be performed, to ensure that a stable value of sigma for each material of the profile is obtained.

For well-investigated sites (see RGs 1.132 and 1.138), the COV should be no less than 0.5. For sites that are not well investigated, the COV for shear modulus shall 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 be less than that value consistent with standard foundation analysis that yields foundation settlement under static loads exceeding design allowables. 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).

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 are 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 preclude 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.

  - The fundamental frequency of the soil (or backfill) stratum should be well below the structural frequencies of interest.

  - 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, including use of frequency-independent soil spring parameters, and the spring and damping coefficients, will be 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) The direct method (DM), in which the foundation impedance is calculated for the free field at all nodes of the excavated soil volume that is discretized into finite elements. These nodes, termed “interaction nodes,” connect the excavated soil volume and the free field soil system to ensure compatible motions.

(2) The subtraction method (SM), in which a simplification is made such that only the nodes on the outer boundary 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 connected to the free-field system, the excavated soil volume may not have compatible motions with the part of the free-field being replaced, especially at frequencies higher than the fundamental frequency of the excavated soil volume. This may lead to limitations in the application of the SM and potential errors if the method is not implemented appropriately.

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 unconservative 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 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 is unaffected 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.

There are advanced analytical methods currently being applied in the nuclear industry to develop seismic responses to high frequency ground motion inputs, incorporating the effect of ground motion incoherency. These methods might be used when a site acceptability determination is performed, as discussed in subsection II.4 of SRP Section 3.7.1. The phenomenon of ground motion incoherency in the free field has been investigated and characterized in terms of coherency functions, 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, 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 Interim Staff Guidance (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 data base 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% reduction
30 Hz and above – 30% reduction
10 to 30 Hz – reduction based on linear variation between 0% at 10 Hz and 30% 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 SRP 3.7.1 II.4.

5. Development of In-Structure Response Spectra. RG 1.122 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 in-structure response spectra 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:

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

(2) The 3 Hz frequency increment in the last row of RG 1.122, Table 1, applies up to the highest frequency of interest. This typically will be the PGA frequency of the design ground response spectrum, which in some cases may significantly exceed 33 Hz.

(3a) When a single set of three artificial time histories is used as the input motion to the supporting structure, the in-structure response spectra are smoothed and broadened in accordance with the provisions of RG 1.122, to account for uncertainty.

(3b) 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 in-structure response spectra 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.I.B of SRP 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 in-structure response spectra generated from the multiple analyses (each of which used one of the multiple design time histories) are used in design.

An evaluation of the statistical correlation between the input ground response spectrum and the output ISRS should also be provided.

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

6. Three Components of Earthquake Motion. RG 1.92 describes acceptable methods for combining the responses due to three components of earthquake 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 earthquake motion are applied simultaneously, using a set of three artificial time histories, the statistical independence of the time histories should be demonstrated. See subsection II.1.B of SRP 3.7.1 for the acceptance criteria to demonstrate statistical independence.

7. <u>Combination of Modal Responses</u>. 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 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.

   When the modal superposition time history method of analysis is used, modal responses are combined algebraically, at each output time step. In accordance with RG 1.92, only modes with natural frequencies less than or equal to the ZPA frequency of the input spectrum are included in the modal superposition time history analysis. The contribution of the higher frequency modes to the total response is calculated by the missing mass approach. Since this contribution is in-phase with the input time history, it is treated as one additional modal response that is scaled by the input time history normalized to the ZPA, and combined algebraically with the modal superposition time history solution at each output time step.

8. <u>Interaction of Non-Category I Structures with Category I SSCs</u>. All non-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-Category I structure should meet at least one of the following criteria:

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

   B. The collapse of the non-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-Category I structure will be analyzed and designed to prevent its failure under SSE conditions

   The disposition of each non-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-Category I structure is acceptable. This should include a description of any additional loads imposed on the 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 Category I SSCs should be described.

   For criterion C, it is necessary to demonstrate that there is no physical interaction between the non-Category I structure and all adjacent Category I SSCs. The maximum permissible displacement of the non-Category I structure in any direction is determined by subtracting the maximum calculated displacement of each adjacent Category I SSC in the direction of the non-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-Category I structure, taking into consideration the potential for sliding and rocking of the non-Category I structure.

A conservative way to address criterion C is to apply a linear elastic analysis to the non-Category I structure, similar to Category I structures. However, depending on the magnitude of the gap between the non-Category I structure and the adjacent Category I SSCs, a limited inelastic response may be permissible for the non-Category I structure, provided the structural integrity can be demonstrated, to ensure no physical interaction between the non-Category I structure and all adjacent 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 SRP 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 will be 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 collapse or interaction with adjacent non-Category I structures. Consequently, DC applicants should provide sufficient analysis and design information concerning interaction of the Non-Category I Structures with Category I SSCs for staff review. In lieu of this, the DC application may 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-Category I Structures with 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 materials for the non-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 SRP section. In addition, for concrete structures, the effect of potential concrete cracking on the structural stiffness should be specifically addressed.

10. Use of Equivalent Vertical Static Factors. The use of equivalent static load factors to calculate vertical response loads for the seismic design of 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 3.7.2.II.1.b of this SRP 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 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 Category I structures.

    To account for accidental torsion, an additional eccentricity of ± 5 percent of the maximum building dimension shall be assumed for both horizontal directions. The magnitude and location of the two eccentricities is 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 unconservative 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, or

    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:

$$\overline{\beta}_j = \{\varphi\}^T \left[\overline{M}\right]\{\varphi\}$$

(1)

$$\beta_j = \frac{\{\varphi\}^T \left[\overline{K}\right]\{\varphi\}}{K^*}$$

(2)

where

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

[K] = assembled stiffness matrix,

$\overline{\beta}_j$ = equivalent modal damping ratio of the j[th] mode,

$[\underline{K}]$, $[\underline{M}]$ = 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

{φ} = 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 a SSI model are reviewed on a case-by-case basis.

14. Determination of Seismic Overturning Moments and Sliding Forces for Seismic Category I Structures. To be acceptable, the determination of the design overturning moment and sliding force should incorporate the following items:

    A. Three components of input motion.

    B. Conservative consideration of the simultaneous action of vertical and horizontal seismic forces.

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

Technical Rationale

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

1. 10 CFR Part 50, GDC 2 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 for 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 in the past. These data shall be used to specify the design requirements of NPP components to be evaluated as part of CP, OL, COL, early site permit (ESP) reviews, or for site parameter envelopes in the case of DCs, thereby ensuring that components important to safety will function in a manner that will maintain the plant in a safe condition.

SRP 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 soil-structure interaction. For additional guidance reference is made to 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 NRC staff, as augmented in this SRP section, to be used in developing two horizontal and one vertical in-structure design response spectra at various floors or other equipment support locations of interest, from the time history motions resulting from the dynamic analysis of the supporting structure. Criteria and/or requirements are also described for considering the interaction of non-Category I structures with 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 requirements provides assurance that seismic Category I systems will be adequately designed to withstand the effects of earthquakes, and thus, will be able to perform their intended safety function.

2. 10 CFR Part 100, Subpart A which is applicable to power reactor site applications before January 10, 1997, refers to Appendix A of this part for seismic criteria. 10 CFR Part 100, Appendix A provides definitions for the OBE and the SSE, and requires that the engineering methods, used to ensure that the required safety functions are maintained during and after the vibratory ground motion associated with the SSE, involve the use of either a suitable dynamic analysis or an appropriate qualification test methodology. 10 CFR Part 100, Appendix A requires that the applicable levels of vibratory ground motion corresponding to the OBE and the SSE are properly defined, and that adequate methods are used to demonstrate that SSCs important to safety can withstand the seismic and other concurrently applied loads.

   10 CFR Part 100, Subpart B which is applicable to power reactor site applications on or after January 10, 1997, refers to10 CFR 100.23 of this part for seismic criteria.10 CFR 100.23 describes the criteria and nature of investigations required to obtain the geologic and seismic data necessary to determine the suitability of the proposed site and the plant design bases. 10 CFR 100.23 also indicates that applications to engineering design are contained in 10 CFR Part 50, Appendix S.

SRP Section 3.7.2 describes acceptable analytical methods for seismic evaluation of seismic Category I structures and systems. The criteria in SRP 3.7.2 provide methods acceptable to the staff for performing static and dynamic seismic analysis of systems. Criteria for the equivalent static load method and criteria for performing response spectrum or time history analyses for dynamic methods are provided.

Meeting these requirements provides assurance that appropriate engineering methods will be used to seismically qualify systems important to safety, and thereby ensure that they will be able to perform their intended safety function when subjected to the SSE and OBE (if applicable).

3. 10 CFR Part 50, Appendix S is applicable to applications for a DC or COL 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 SSCs will remain functional and within applicable stress, strain, and deformation limits. The required safety functions of SSCs must be assured during and after the vibratory 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 the applicable stress, strain, and deformation limits are satisfied.

   SRP 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 SRP Section 3.8. The criteria in SRP Section 3.7.2 ensure that the effects of the three components of earthquake 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 requirements 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

The reviewer will select material from the procedures described below, as may be appropriate for a particular case.

These review procedures are based on the identified SRP 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.

1. Seismic Analysis Methods. For all 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 SRP section. If empirical methods or tests are used in lieu of analysis for any 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.

2. Natural Frequencies and Response Loads. The summary of natural frequencies and response loads is reviewed for compliance with the acceptance criteria in subsection II.2 of this SRP section.

3. 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 SRP 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 SRP section.

4. 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 SRP section. Typical mathematical models for SSI analysis are reviewed to ensure the adequacy of the representation in accordance with subsection II.4 of this SRP 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.

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

6. Three Components of Earthquake Motion. The procedures by which the three components of earthquake motion are considered in determining the seismic response of SSCs are reviewed to determine compliance with the acceptance criteria of subsection II.6 of this SRP section.

7. Combination of Modal Responses. The procedures for combining modal responses are reviewed to determine compliance with the acceptance criteria of subsection II.7 of this SRP section.

8. Interaction of Non-Category I Structures with Category I SSCs. The design and analysis criteria for interaction of non-Category I structures with Category I SSCs are reviewed to ensure compliance with the acceptance criteria of subsection II.8 of this SRP section.

9. 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 determine compliance with the acceptance criteria of subsection II.9 of this SRP section. Among the various structural parameters analyzed, the effect of potential concrete cracking on structural stiffness should be addressed.

10. Use of Equivalent Vertical Static Factors. Use of constant static factors as response loads in the vertical direction for the seismic design of any Category I SSC, in lieu of a detailed dynamic method, is reviewed to determine compliance with the acceptance criteria of subsection II.10 of this SRP section.

11. Methods Used to Account for Torsional Effects. The methods of seismic analysis are reviewed to determine that the torsional effects of vibration are incorporated, in compliance with the acceptance criteria of subsection II.11 of the SRP section. Justification provided by the applicant for the use of any approximate method to account for torsional effects is reviewed, to ensure that it results in a conservative design.

12. Comparison of Responses. Where applicable, the responses obtained from both time history and response spectrum methods at selected points in major 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.

13. Analysis Procedure for Damping. 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 SRP section.

14. Determination of Seismic Overturning Moments and Sliding Forces for Category I Structures. The analysis methods to calculate seismic overturning moments and sliding forces are reviewed to determine compliance with the acceptance criteria of subsection II.14 of this SRP section.

15. Design Certification and Combined License Reviews. 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 Final Safety Analysis Report (FSAR) meets the acceptance criteria. DCs have referred to the FSAR as the Design Control Document (DCD). The reviewer should also consider the appropriateness of identified COL action items. The reviewer may identify additional COL action items; however, to ensure 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 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 safety evaluation report. 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, 10 CFR Part 100, Subpart A (for applications received before January 10, 1997, and 10 CFR Part 100, Subpart B (for applications received on or after January 10, 1997). This conclusion is based on the following: The applicant has met the requirements of GDC 2 and 10 CFR Part 100, Appendix A or 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 for the most severe earthquake recorded for the site with an appropriate margin (GDC 2). Consideration of two levels of earthquakes (10 CFR Part 100, Appendix A or 10 CFR Part 50, Appendix S),

2. Appropriate combination of the effects of normal and accident conditions with the effect of the natural phenomena,

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

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 100, Appendix A or 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 as per SRP Section 3.7.1. The combination of earthquake-resultant loads with those resulting from normal and accident conditions in the design of Category I structures as specified in SRP Sections 3.8.1 through 3.8.5 will be 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 Category I SSCs. It included review of procedures for modeling, seismic SSI, development of floor response spectra, inclusion of torsional effects, seismic analysis of Category I concrete dams, evaluation of Category I structure overturning, and determination of composite damping. The review included design criteria and procedures for evaluation of the interaction of non-Category I structures with Category I structures and the effects of parameter variations on floor response spectra.

   The review also included criteria and seismic analysis procedures for Category I buried piping outside containment and above-ground Category I tanks.

The system and subsystem analyses are performed by the applicant on an elastic and linear basis. Time history methods form the bases for the analyses of all major Category I SSCs. When the modal response spectrum method is used, the methods used in combining modal responses are in conformance with the regulatory positions in RG 1.92, if used, alternate methods have been evaluated and found to be acceptable. Floor spectra inputs to be used for design and test verifications of SSCs are generated from the time history method, and they are in conformance with the position of RG 1.122, as augmented in this SRP section. 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 are considered.

A coupled structure and soil model is used to evaluate SSI effects upon seismic responses. Appropriate nonlinear stress-strain and damping relationships for the soil are considered in the analysis. We conclude that the use of the seismic structural analysis procedures and criteria delineated above by the applicant provides an acceptable basis for the seismic design which is in conformance with the requirements of item 3 listed above.

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 SRP section.

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

V. IMPLEMENTATION

The following is intended to provide guidance to applicants and licensees regarding the NRC staff's plans for using this SRP section.

The staff will use this SRP section in performing safety evaluations of DC applications and license applications submitted by applicants pursuant to 10 CFR Part 50 or 10 CFR Part 52. Except when the applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the staff will use the method described herein to evaluate conformance with Commission regulations.

The provisions of this SRP section apply to reviews of applications submitted six months or more after the date of issuance of this SRP section, unless superseded by a later revision.

Implementation schedules for conformance to parts of the method discussed herein are contained in the referenced regulatory guides.

Operating license and final design approval applications, whose CP and PDA reviews were conducted after August of 1989 but prior to the issuance of Revision 3 to SRP Section 3.7.2, will be reviewed in accordance with the acceptance criteria given in the SRP Section 3.7.2, Revision 2, dated August 1989. Operating license and final design approval applications, whose CP and PDA reviews were conducted prior to the issuance of this Revision 2 to SRP

Section 3.7.2, will be reviewed in accordance with the acceptance criteria given in the SRP Section 3.7.2, Revision 1, dated July 1981.

VI. REFERENCES

1. 10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities.”

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

3. 10 CFR Part 50, Appendix S, “Earthquake Engineering Criteria for Nuclear Power Plants.”

4. 10 CFR Part 52, “Early Site Permits; Standard Design Certifications; and Combined Licenses for Nuclear Power Plants."

5. 10 CFR Part 100, Subpart A, "Evaluation Factors for Stationary Power Reactor Site Applications before January 10, 1997 and for Test Reactors.”

6. 10 CFR Part 100, Subpart B, "Evaluation Factors for Stationary Power Reactor Site Applications on or After January 10, 1997.”

7. 10 CFR Part 100, Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants.”

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

9. DC/COL-ISG-01, “Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications.” May 19, 2008.

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

11. NUREG/CP-0054, "Proceedings of the Workshop on Soil-Structure Interaction,” Bethesda, MD, June 16-18, 1986.

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

13. RG 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants."

14. RG 1.70, “Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants.”

15. RG 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis."

14. RG 1.122, "Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components."

15. RG 1.132, “Site Investigations for Foundations of Nuclear Power Plants”

16. RG 1.138, “Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants”

17. RG 1.206, “Combined License Applications for Nuclear Power Plants (LWR Edition).”

18. RG 1.61, "Damping Values for Seismic Design of Nuclear Power Plants,”

APPENDIX A

AUDIT GUIDELINES FOR SRP SECTION 3.7 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 review pertinent technical information that 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 unresolved technical issues. The audit results form part of the technical basis for the staff's final safety determination.

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 NRC lead technical reviewer. The audit agenda is forwarded to the applicant by the LPM, at least two 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, comprised 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 request 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, four 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 DCD.

(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 confirmatory seismic analyses. (first audit)

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

(6) Identify and document any new outstanding issues (new RAIs) resulting from (1) through (5) above.

6. <u>Conduct of the Audit</u>

(1) Entrance Meeting

An entrance meeting will be 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 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 three (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 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:

1. Development of the ground motion time histories to match the design basis ground response spectrum.

2. Modeling of soil properties.

3. Modal properties of the structural models; confirmation of adequate refinement relative to the frequency content of the design basis ground response spectrum.

4. Methodologies employed (computer codes, computer models) to conduct seismic analysis, including soil structure interaction (SSI) effects.

5. In-structure response spectra

(3) Exit Meeting

An exit meeting will be 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. One (1) 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 unresolved issues 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.

PAPERWORK REDUCTION ACT STATEMENT

The information collections contained in the Standard Review Plan are covered by the requirements of 10 CFR Part 50 and 10 CFR Part 52, and were approved by the Office of Management and Budget, approval number 3150-0011 and 3150-0151.

PUBLIC PROTECTION NOTIFICATION

The NRC may not conduct or sponsor, and a person is not required to respond to, a request for information or an information collection requirement unless the requesting document displays a currently valid OMB control number.

SRP Section 3.7.2
"Seismic System Analysis"

Description of Changes

This SRP section affirms the technical accuracy and adequacy of the guidance previously provided in Revision 3, dated March 2007 of this SRP. See ADAMS Accession No. ML070640311.

I. AREAS OF REVIEW

1. Revised the designation of the primary review responsibility to be the organization responsible for structural reviews.

2. Enhanced Item 4 "Soil-Structure Interaction" to indicate review of generic site profiles for DC application. See item 5 below (under "Acceptance Criteria") for the technical rationale for this change.

II. ACCEPTANCE CRITERIA

1. Enhanced SRP Section 3.7.2 II.3.C by adding item (iv) regarding modeling of structures for the effects of concrete cracking. The technical rationale for this change is as follows.

   When developing mathematical models to perform seismic analysis of concrete structures, the stiffness of the structural elements is affected by the degree of concrete cracking. To ensure that the mathematical models realistically represent the concrete structures, the SRP guidance was enhanced to provide additional criteria on how to consider the effects of concrete cracking on the structural stiffness of members used in the models.

   Concrete cracking can reduce the stiffness and increase damping of structures, which would reduce the frequencies of the structure and thereby may affect the seismic response analysis. In past licensing applications, questions have arisen regarding the proper consideration of the effects of concrete cracking when performing seismic analysis of structures. Part of this reflected a need for additional guidance in the SRP on acceptable methods for treating the effects of concrete cracking.

   It is well recognized that the use of the appropriate stiffness 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). The stiffness representation for reinforced concrete structures depends on the level of concrete cracking which is a function of the level of stress due to the most critical load combination. Concrete cracking can affect the membrane, bending, and shear stiffness of the members which should be considered in the mathematical model. Because concrete cracking phenomena are complex and depend on a number of factors, the approach used to represent structural stiffness should be shown to be conservative. An acceptable approach for representing 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 the ASCE/SEI 43-05 standard (e.g., 0.5 for cracked walls for flexure and shear).

For the design of structures, the responses (e.g., member forces, displacements, soil bearing pressures) are typically determined from a separate detailed finite element analysis. The effects of concrete cracking in these finite element analyses should be considered in a manner consistent with the representation of cracking in the SSI analysis. Further guidance on whether cracked concrete properties should be considered in the design for seismic Category I structures is provided in the acceptance criteria for design and analysis procedures presented in SRP Sections 3.8.1 and 3.8.3 through 3.8.5.

2. Enhanced SRP Section 3.7.2 II.4 "Soil-Structure Interaction" by adding acceptance criteria related to foundation uplift. The technical rationale for this change is as follows.

    The seismic analysis used in the design of Seismic Category I structures requires consideration of the potential uplift of the foundation from the supporting soil media. Limiting the foundation uplift is necessary to ensure the validity of the SSI analysis that is based on linear methodologies. Consideration of foundation uplift is also important in order to appropriately estimate the overturning moments induced by the seismic input and the soil bearing pressures at the foundation toe.

    SRP Section 3.7.2 II.4 indicates that sensitivity studies are needed to identify the potential for separation and sliding of soil from sidewalls, among other issues, and to assist in judging the adequacy of the final results of the SSI analyses. SRP Section 3.8.5II.4.D provides guidance on how to define the dead load for uplift evaluations, including the treatment of the stored water in internal water pools inside the structures. Other SRP 3.8.5 subsections provide guidance on seismic stability evaluations, foundation design, and maximum toe bearing pressures. However, the SRP does not provide specific guidance on permissible levels of foundation uplift to be considered in the SSI analysis and the foundation design.

    The staff performed the literature search and identified that only the Japanese codes specifically address foundation uplifting effect in design of nuclear facilities. The proposed SRP revision is based on Japanese design criteria, which presented a comprehensive set of criteria for assessing foundation uplift effect. The Japanese codes utilize the ground contact ratio concept. The ground contact ratio is defined as the ratio of the minimum area of the foundation in contact with the soil to the total area of the foundation. The seismic response computed over the entire duration of the seismic ground motion needs to be considered to determine the minimum value of this ratio.

    The proposed SRP revision sets a limit of 80 percent to the ground contact ratio to accept the results from the linear SSI analysis. The corresponding limit in the Japanese criteria is 75 percent (Section 3.5.5.4 in the Japanese design code JAEC 4601-2008).

    The proposed revision of SRP Section 3.7.2 addresses the validity of linear SSI analysis if some foundation uplift occurs. If the limit of 80 percent is not met then the nonlinearity due to the foundation uplift should be assessed, and if found important, then it should be accounted for in the seismic design, which is then reviewed on a case-by-case basis. Additional guidance for foundation design is incorporated in a proposed revision to SRP Section 3.8.5.

3. Enhanced SRP Section 3.7.2 II.4 “Soil-Structure Interaction” by adding acceptance criteria related to finite element discretization of excavated soil volume. See item 6 below for the technical rationale for this change, which is associated with the additional acceptance criteria for SSI analysis of embedded structures using the substructure approach (direct vs. subtraction methods).

4. Enhanced SRP Section 3.7.2 II.4 “Soil-Structure Interaction” by adding acceptance criteria related to soil properties in DC and COL application. See item 5 below for the technical rationale for this change.

5. Enhanced SRP Section 3.7.2 II.4 “Soil-Structure Interaction” by adding acceptance criteria related to the distribution of site profiles and their relationship to the amplified CSDRS. The technical rationale for this change is as follows.

   In accordance with 10 CFR 52.47 (a) (1) and (2), the DC applicant defines the postulated site parameters which include the site profiles to be used in the seismic analysis of the SSCs. The applicant defines the site profiles that are specifically applicable to the DC application. Based on the assumed site profiles, a free-field input ground motion, referred to as the CSDRS is established, which should be appropriate to the postulated site profiles. Together the postulated soil profiles and CSDRS define the seismic design basis for the plant.

   The CSDRS should be appropriate to the postulated site profiles in frequency content because the site profile frequency characteristics determine the amplification of the input ground motion through the site. Using a seismic SSI analysis, the seismic ground motion input spectra is propagated through the site profiles into the structure in terms of seismic response or demands for design of structural members and supported equipment. The amplification of the input ground motion occurs at the profile column frequencies. Therefore, a CSDRS containing significant amplification at frequencies other than those of the profile columns will not be amplified in structural demands through the postulated site profiles. The proposed criterion ensures that the CSDRS should be shown to be appropriate for the postulated site profiles in frequency content by demonstrating that there is a reasonable distribution of the site profile column frequencies over the amplified portion of the CSDRS.

   The proposed enhancement improves the SRP guidance in the following aspects: (1) it includes the consideration of the generic site profiles in the scope of the review and the corresponding appropriate CSDRS to ensure an adequate seismic design basis; (2) it clarifies that for a COL application referencing a standard plant design, where the site-specific GMRS fall below the standard plant CSDRS, it is also 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; and (3) for a DC application, the CSDRS should be shown to be appropriate for these postulated site profiles in frequency content by demonstrating that there is a reasonable distribution of the site profile column frequencies over the amplified portion of the CSDRS.

6. Enhanced SRP Section 3.7.2 II.4 “Soil-Structure Interaction” by adding acceptance criteria related to SSI analysis of embedded structures using the substructure approach (direct vs. subtraction methods). The technical rationale for this change is as follows.

   For the case of embedded structures, two analytic methods have been used in SSI computations based on the substructure approach. The first method, referred to as the flexible volume or direct method (DM), is the most reliable but also the most computationally intensive method. The DM incorporates all nodes of the finite element mesh for the excavated below-grade zone of the embedded structure (termed the interaction nodes) in the solution. The second method, known as the subtraction method (SM), uses an approximate simplification that yields significant reductions in computational effort. It reduces the number of the interaction nodes to only those on the boundary of the excavated zone and assumes that the remaining interior nodes do not need to be connected to the boundary nodes. However, recent SSI analyses performed for certain Department of Energy facilities identified limitations associated with the SM. It was found that, if not implemented properly, the application of the SM to the SSI analysis of embedded structures may result in erroneous and unconservative SSI responses when compared to the DM.

   To identify limitations and mitigate potential errors associated with the SM, and to ensure that a conservative seismic analysis is performed, SRP Section 3.7.2 guidance regarding SSI analysis was enhanced to provide additional criteria for reviewing SSI analysis of embedded structures performed using the SM.

7. Enhanced SRP Section 3.7.2 II.4 “Soil-Structure Interaction” by adding acceptance criteria related to SSI analysis incorporating the effects of ground motion incoherency. The technical rationale for this change is as follows.

   Advanced analytical methods are being applied in the nuclear industry, to develop seismic responses to high frequency ground motion inputs, incorporating the effect of ground motion incoherency. The phenomenon of ground motion incoherency in the free field has been investigated and characterized in terms of coherency functions, based on recorded earthquake data collected from dense array seismic data. The ground motion incoherency effect on structural response is considered by incorporating a coherency function in analytical methods for SSI analyses. SSI analyses based on analytical methods that consider ground motion incoherency generally reduce structural response in high frequencies, compared to the response based on the traditional assumption of ground motion coherency. However, the effect of incoherent ground motion may cause an increase in motions associated with overturning and torsional structural responses.

   Although the development of the coherency function incorporated a degree of conservatism which was intended to compensate to a certain extent for the uncertainty associated with the lack of data for the high frequency hard rock sites in the Eastern US and the ground motion variability with depth, it is important to recognize that the reductions in structural response due to ground motion incoherencies are quantified based on analytical models which utilize the coherency function described in DC/COL-

ISG-01 and also recognize that their application to licensing activities is rather limited to date. In addition, there are no field tests available to confirm the extent to which the incoherent free field ground motion reduces the structural response in terms of in-structure response spectra and member forces. Therefore, it is reasonable to place a limit on the reductions due to incoherency at this time. The staff will reconsider the limit when more information and associated data become available to better quantify the in-structure response reductions due to ground motion incoherency effects.

The EPRI performed analytical studies which formed the basis for the staff's guidance in DC/COL-ISG-01. These studies compared coherent ISRS results to incoherent ISRS results, based on the NRC-accepted coherency function. The structural model used has stick model representations of the AP1000 steel containment vessel, shield building, and containment internal structures, sitting on a large basemat. Review of the comparisons indicated that the ISRS are generally similar up to about 10 Hz. Above 10 Hz, there is generally a gradually increasing difference. Above 30 Hz, differences as high as 40-50% can be observed. The staff has accepted this level of reductions on a case-by-case review along with independent confirmatory analysis.

Based on the uncertainties associated with the coherency function described above and the limited experience in its implementation to date, the staff has determined that it is reasonable to impose limits on the maximum acceptable reductions between coherent results and incoherent results. These reductions generally are in line with the EPRI studies. It should be noted that the proposed criteria allows for larger ISRS reductions than the specified limits if sufficient technical information is provided to support the larger reductions. The staff reviews and accepts the technical justifications for larger reductions on a case-by-case basis.

8. Enhanced SRP Section 3.7.2 II.8 "Interaction of Non-Category I Structures with Category I SSCs" by revising acceptance criteria related to Criterion C. The technical rationale for this change is as follows.

The objective of Criterion C is to demonstrate that failure under SSE conditions will be prevented. What constitutes "failure" is dependent on the proximity of the non-Category I structure to Category I SSCs.

As an example, for a non-Category I structure in proximity to a Category I structure, the absolute sum of the seismic displacements of the two structures needs to be less than the as-designed gap between the structures for the entire height of the structures, in order to satisfy criterion C.

If the structures are in very close proximity, it may be necessary to apply Category I structural design criteria to the non-Category I structure, in order to satisfy Criterion C.

If there is an appreciable gap between the two structures, then a relaxation of Category I structural design criteria may be appropriate, provided it can be demonstrated that (1) the non-Category I structure is in a stable limit state (no gross failure), and (2) the as-designed gap (considering construction tolerances) between the structures is large enough to accommodate the absolute sum of the seismic displacements of the two structures.

The ASCE 43-05 standard presents a graded approach to design/analysis of structures for loading combinations that include seismic loads. In accordance with ASCE 43-05, nuclear seismic Category I structures require the most stringent design criteria; namely, a linear elastic limit state. This is consistent with NRC guidance for design/analysis of Category I structures. ASCE 43-05 also addresses design/analysis of structures of less critical functions, allowing response beyond the elastic limit state, to a safe and predictable inelastic limit state. Such an approach is potentially applicable to satisfying Approach C, where there is sufficient gap to accommodate increased displacement of the non-Category I structure.

VI. REFERENCES

1. Added reference to ASCE/SEI 43-05.

2. Added reference to Interim Staff Guidance 01 (DC/COL-ISG-01).