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SRP UPDATE TO ENHANCE GUIDANCE ON SEISMIC AND STRUCTURAL DESIGN REVIEWS

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ABSTRACT

NUREG-0800, Standard Review Plan (SRP), Sections 3.7 and 3.8 provide guidance for review of reactor applications related to the seismic analysis and structural design of seismic Category I structures and foundations, including containment. The last major revision to these SRP sections, which incorporated changes required for anticipated new reactor applications filed under Title10 of the *Code of Federal Regulation* (CFR) Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants," was completed in 2007. Since then, the staff has utilized these SRP sections to complete the review of several design certification (DC) applications and combined license (COL) applications under 10 CFR Part 52. Because of the differences in the licensing process between 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," and Part 52, the seismic analysis and structural design under Part 52 require different approaches from those used previously. These differences have resulted in certain technical issues and challenges to both the applicants and the staff reviewers. Nuclear power plant (NPP) structures are designed to withstand both internally and externally initiated hazards. For internal events, such as internal floods and loss-of-coolant accidents (LOCAs), the design approaches between Part 50 and Part 52 facilities are essentially the same. However, for externally initiated events such as wind, snow, and earthquake, different approaches to structural analyses and designs may be required for Part 52 applications as opposed to Part 50, because of the distinct differences in the licensing process. Externally initiated events, such as earthquakes, are inherently site-dependent which can be objectively addressed in site-specific applications under Part 50. However, the site dependent aspects of the external events pose challenges to standard plant designs under Part 52 process.

Because of the staff's review of recent DC and COL applications under Part 52, the staff found a number of technical issues related to seismic analysis and structural designs. To a large extent, the issues were related to the need to develop a standard (generic) plant design that can be safely built at locations with different site characteristics. These issues often led to the issuance of more requests for additional information (RAIs) and lengthened the staff's review process.

The NRC staff recently issued SRP Revision 4 to include enhancements to supply further guidance on technical issues associated with seismic and structural designs under Part 52 licensing process. This paper provides overview of the enhancements included in Revision 4 to the SRP and discusses related technical rationales for changes to SRP acceptance criteria. With these enhancements, it is expected that reviews related to seismic analysis and designs should be improved, and become more effective and efficient in the future.

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INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) technical report NUREG–0800, “Standard Review Plan (SRP) for the Review of Safety Analysis Reports (SAR) for Nuclear Power Plants: LWR Edition,” Sections 3.7 and 3.8 provide guidance for the seismic analysis and structural designs of the containment and other seismic Category I structures and foundations. The NRC issued a major revision to these SRP sections in 2007 (before Revision 4) for use in the review of design certification (DC) applications and combined license (COL) applications under Title 10 of the Code of Federal Regulations (10 CFR) Part 52. Because of the differences in the licensing process between 10 CFR Part 50 and Part 52, the seismic analysis and structural design under Part 52 required different approaches from those used previously in applications under Part 50. These differences have resulted in certain technical issues and challenges to both applicants and reviewers, which the 2007 revision to SRP intended to address.

General Design Criteria (GDC) of Appendix A, “General Design Criteria for Nuclear Power Plants,” to 10 CFR Part 50 provide the regulatory requirements to ensure that nuclear power plant (NPP) structures, systems, and components (SSCs) important to safety be designed to adequately withstand both internally and externally initiated challenges. For internal events such as internal floods and loss-of-coolant accidents (LOCAs), the design approach for Part 50 and Part 52 facilities is essentially the same. However, for externally initiated events such as wind, snow, and earthquake, different approaches to structural analyses and designs may be taken for Part 52 applications as opposed to Part 50 facilities, because of the distinct differences in the licensing process. Externally initiated events such as earthquakes are inherently site-specific and dependent on site-specific characteristics. Design of a nuclear power plant under Part 50 against natural phenomena hazards can be achieved on a site-specific basis. However, standard plants under Part 52 process are designed based on the site parameters (assumed site characteristics) independent of any specific site. Considering the strong dependency of natural phenomena hazards on site-specific conditions, the design approach for natural phenomena hazards based on generic site conditions, although with many advantages such as achieving standardized design that can be located at different sites, presents challenges to both the designer and regulator and the resulting design could also be overly conservative.

As NRC staff has made significant progress in the review of DC and COL applications under Part 52, the staff also found technical issues related to seismic analysis and structural designs that can challenge the review progress. The staff recently considered lessons learned from the past reviews and interactions with applicants in resolving significant technical issues to re-examine the review guidance to identify areas where technical enhancements could be made to provide better review guidance and to facilitate issue resolutions. To a large extent, the issues identified are related to the technical aspects associated with standard (generic) plant designs that can be built based on assumed site parameters enveloping potential future site conditions in the United States. These issues had often led to the issuance of more requests for additional information (RAIs) and had lengthened the review process. The lessons learned from past application reviews can be used to further clarify or enhance the review guidance which could expedite issue resolutions and increase the efficiency and effectiveness of future application reviews.

To this end, NRC staff recently issued Revision 4 to SRP, Sections 3.7 and 3.8 to incorporate the lessons learned to date and to offer additional technical guidance for application reviews. This paper provides an overview of the enhancements included in Revision 4 to the SRP and discusses related technical rationales for enhanced SRP acceptance criteria. With these enhancements, the staff expects that the resolution of technical issues related to seismic analysis and designs should be expedited, resulting in more effective and efficient reviews in the future.

PROCESS FOR REVISION 4 TO SRP SECTIONS 3.7 AND 3.8

As the staff applied the 2007 edition of SRP 3.7 and 3.8 to the review of DC and COL applications under 10 CFR Part 52, technical issues related to the seismic analysis and structural designs arose across the applications that challenged both applicants and the staff. Resolution of these issues often took significant time and resources resulting in prolonged application reviews. To address these technical issues, NRC staff initiated an effort to identify technical areas where the staff guidance could be enhanced to articulate the technical positions to ensure expedited resolution of technical issues in the review process.

The staff developed a lessons learned process for enhancing SRP guidance for seismic and structural reviews with the following objectives: (1) to identify the key analysis and design challenges that arose from the seismic and civil structural reviews of new reactor applications under the Part 52 process, (2) to describe the underlying key technical issues, (3) to enhance SRP acceptance criteria to address these issues, and (4) to articulate technical rationale for SRP enhancements. Specifically, some key issues related to seismic analysis and structural designs were found, which led to improvements to SRP acceptance criteria. During the process of the revising SRP, the staff considered lessons learned from past application reviews, interacted with and solicited feedback from the industry, applicants as well as other stakeholders to ensure adequate alignment on the enhancements to SRP acceptance criteria. The staff also developed technical rationales to explain why the SRP acceptance criteria should be enhanced and offered the technical basis and/or rationale for the enhancements by Xu, et al (2014). The enhanced SRP criteria are also intended to improve clarity of technical positions and ensure a more uniform review process that will benefit the nuclear industry and better assist the staff in future technical reviews of applications.

With these enhancements, the staff expects that both applicants and reviewers will be better able to ascertain technical issues related to seismic analysis and structural designs in the preparation and review of future applications, which should lead to a more effective and efficient review process.

OVERVIEW OF SRP ENHACENMENTS AND RATIONALES

Revision 4 to SRP Sections 3.7 and 3.8 has incorporated technical enhancements to address areas of seismic and structural issues where technical challenges were noted during the review process of past DC and COL applications. The enhancements incorporated in the SRP can be grouped in the categories to address issues related to the seismic analyses and the designs. As these technical issues were extensively discussed between the staff and the applicants during new reactor application reviews, the staff considered SRP enhancements to address these issues to ensure their consistency with the resolution of the technical issues reached and to reflect the lessons learned during application reviews. The following paragraphs provide a brief overview of key SRP enhancements and technical rationales. Because of the space limitation, other enhancements incorporated in SRP and detailed discussions can be found in the staff developed rationale document by Xu, et al (2014).

Most of the enhancements were identified and carried out in the SRP with respect to the seismic analysis as it often involves complex technical issues requiring special treatments such as linear vs. nonlinear, coherent motion vs. incoherent motion, interaction issues, etc. Therefore, key aspects of the enhancements related to seismic analysis are discussed first followed by a discussion of two design issues where SRP acceptance criteria were strengthened.

Seismic uplift in soil-structure interaction analysis

The seismic analysis considering soil-structure interaction (SSI) effect has been an established process for the seismic design of NPP structures. The SSI analysis is typically performed based on linear treatment of the soil-structure system such as the sub-structuring approach, for example, Wolf (1973). The linear treatment assumes perfect bonding between soil and structure at their interfaces. However, such condition may not always be met especially for situations where strong ground motions are considered such as the safe shutdown earthquake (SSE) for NPP seismic design.

Justifications for linear SSI with permissible seismic uplift (vertical separation between structural foundation and the supporting soil) often require multiple rounds of requests for additional information (RAIs) in application reviews. To address this issue and facilitate application review, SRP Revision 4, Section 3.7.2 included this guidance: "Linear SSI analysis methods are acceptable if the ground contact ratio is equal to or greater than 80 percent. The ground contact ratio can be calculated from the linear SSI analysis using the minimum basemat area that remains in compression with the soil. If the ratio is less than 80 percent, then the effect of the nonlinearity due to the foundation uplift should be evaluated. If the uplift effect on structural responses (e.g., in-structure response spectra, member forces, soil bearing pressure, and building displacements, etc.) is found to be significant (e.g., an increase in response of more than 10 percent), then the uplift effect should be accounted for in the seismic design, which is reviewed on a case-by-case basis."

This criterion was established based on past studies in the literature as well as the Japanese design code JAEC 4601-2008 (2008) which provides quantitative provisions for considering seismic uplift effect in the SSI. Although the Japanese practice imposes uplift limit of 75-percent for performing linear SSI, the staff determined that 80-percent criterion is appropriate to the U.S. practice. This is because the Japanese criteria refer to often simplified SSI approaches with additional conservatism while in the United States. the SSI is typically performed using detailed more realistic finite element methods. In addition, the 80 percent limit is consistent with the findings of previous analytical studies (e.g., Wolf (1976) and Miller (1986)).

Seismic stability evaluation for design of structures

The SRP provisions before Revision 4 relied on a static approach to evaluate the seismic stability of the structures. When structures are subject to high seismic loads and bounding soil properties, as is the case in DCs or for plants in high seismicity regions, achieving the needed factors of safety for sliding and overturning may be more difficult to demonstrate using the static approach. Several recent DC applicants have resorted to more complex analytical methods to reduce the conservatism inherent in the static approach. These methods rely on time history analyses using three directions of statistically-independent seismic loadings applied simultaneously. This approach eliminates the static analysis assumption that the maximum vertical and maximum horizontal demand forces occur at the same time. The oscillatory nature of the response in a seismic time history analysis may demonstrate that the specified factors of safety are maintained at each instant in time. If the linear time history analysis shows that some sliding and uplift may occur, then a nonlinear time history analysis can be performed to include these effects.

To offer guidance on staff's expectations when the time history evaluations discussed above are performed, SRP Section 3.8.5 was enhanced to address the following issues:

- calculation of factor of safety (FOS) in linear stability evaluation
- stability evaluation using nonlinear analysis including selection of multiple time histories
- adequacy of the mathematical model

- enhancement of criteria for selection of appropriate friction values
- acceptance criteria if minimal sliding displacements do occur

The enhanced SRP criteria aligned the review guidance with the latest technology and methods for the stability analyses of NPP structures.

Interaction of non-seismic Category I structures with seismic Category I SSCs

Non-seismic Category I structures are typically designed to a less restrictive criteria than seismic Category I structures. However, if the non-seismic Category I structures are in close proximity to seismic Category I SSCs, then the failure of the non-seismic Category I structures could impair the safety function of seismic Category I SSCs, which is often referred to as seismic II/I interaction.

However, SRP Revision 3, Section 3.7.2.8 acceptance criteria for II/I interaction stated “the non-Category I structure will be analyzed and designed to prevent its failure under SSE conditions, such that the margin of safety is equivalent to that of Category I structures.” Such criteria may be too restrictive for the design of non-seismic Category I structures, since it apparently invokes the same design criteria as is applicable to seismic Category I structures.

Although adherence to seismic Category I design criteria is acceptable, the SRP acceptance criteria was enhanced to allow other alternatives for addressing II/I interaction without being overly restrictive. The key aspect of the alternative approaches is an appropriate gap between the non-seismic Category I structure and seismic Category I SSCs which could permit lesser limit state for the II/I evaluation than for the design such as the graded approach described in the American Society of Civil Engineers (ASCE) 43-05 (2005). 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 the SRP for design and analysis of seismic Category I structures. ASCE 43-05 also addresses design and analysis of structures of less critical functions, allowing response beyond the elastic limit state, to a safe and predictable inelastic limit state. These safe and predictable inelastic limit states could be used to determine the seismic II/I interaction provided that appropriate gaps between these structures are adequately established.

Cracking effect on seismic analysis of concrete structures

Consideration of cracking effect is an important aspect of the seismic analysis for reinforced concrete structures. Regulatory Guide (RG) 1.61provides material damping values associated with the response levels corresponding to the SSE and operating basis earthquake (OBE). It is recognized that an SSE analysis for reinforced concrete structures based on OBE damping always leads to conservative in-structure response spectra (ISRS) but may be too restrictive for the design. Criteria for developing ISRS based on SSE damping values are needed for reinforced concrete structures especially for DC designs. To this end, SRP Revision 4 included the enhancement that for a DC design, where the design-basis ISRS represent the envelope of the in-structure responses obtained from multiple analyses conducted to consider the range of expected site soil conditions associated with the 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 un-cracked concrete properties with OBE damping values in Table 2 of RG 1.61, are acceptable to develop ISRS.

The rationale for this criterion is as follows. When generating ISRS for a DC, two situations arise in considering the site conditions. In the first situation, in which 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 CSDRS, the cracked concrete properties can be used along with corresponding SSE damping values in Table 1 of RG 1.61, Revision 1. This approach is acceptable because multiple SSI analyses are performed on a range of soil conditions associated with the CSDRS and the results are enveloped which lead to conservative ISRS. The second situation deals with a single site condition where site-specific HRHF spectra are used as part of the CSDRS. In this case, the use of un-cracked concrete properties with OBE damping values in Table 2 of RG 1.61, Revision 1, is acceptable to develop ISRS. This approach is appropriate because the site-specific HRHF spectra should not cause cracking in the structural design based on the CSDRS, because the HRHF spectra typically have frequencies in the amplified region above the frequencies of structures. Therefore, the use of OBE damping with un-cracked concrete properties ensures damping compatible structural response, which is consistent with the regulatory position C.1.2 of RG 1.61, Revision 1.

Issues with SASSI subtraction method

The System for Analysis of Soil-Structure Interaction (SASSI) program, which Lysmer et al. (1981, 1999) developed originally, is an effective soil-structure interaction (SSI) analysis tool based on the sub-structuring approach. Several commercial versions of SASSI have been used to perform seismic analyses in support of DC and COL applications.

For the case of embedded structures, two analytic approaches are used in SSI computations performed with SASSI. The first approach, referred to as the flexible volume or direct method (DM), is the more reliable but also the more 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 the 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, SSI analyses performed for certain U.S. Department of Energy (DOE) facilities noted 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 potentially result in erroneous and un-conservative SSI responses when compared to the DM.

To find limitations and mitigate potential errors associated with the SM, and to ensure that a conservative seismic analysis is performed, Revision 4 to SRP Section 3.7.2 included additional guidance on SSI analysis to provide criteria for reviewing SSI analysis of embedded structures performed using the SM. The additional guidance aims at addressing issues associated with the sub-structuring algorithm related to the possible incompatible motions between the excavated soil volume and the portion of the free field being replaced. The SM as an approximate solution can potentially affect the SSI response in two aspects. First, the vibration modes of the excavated soil volume in the SM model may be spurious. For ground motion inputs with dominant frequencies higher than the fundamental frequency of the excavated soil volume, these spurious vibration modes may be excited and participate in the dynamic response, which would likely have an effect on the computed SSI response. Second, the computed SSI response could either be increased or reduced depending on whether the excavated soil volume moves in-phase or out-of-phase with the superstructure. This can be found in the pattern of highly oscillatory behavior seen in typical SSI response computed using the SM as opposed to the DM.

The limitations of the SM can be alleviated by connecting additional nodes of the excavated soil volume to the part of the free field being replaced. This is accomplished in the so-called modified SM (MSM); however, as more nodes are added to the MSM, the computational effort is also increased. It should be noted that the MSM can reduce but not eliminate the incompatibility issue associated with the SM. In summary, the issues associated with the SM are strongly dependent on (1) the characteristics of the ground motion input and (2) the particular soil-structure configurations being analyzed. Therefore, specific guidance is provided to ensure that eigenvalue characteristics of the excavated soil volume are well understood to provide an indication of the frequencies at which the spurious vibration modes are likely to occur. For example, if it is found that the lowest natural frequency of the excavated soil volume is greater than the zero period acceleration (ZPA) frequency of the ground motion inputs, then the incompatibility issue with the SM is not likely to affect the SSI response. Guidance is also provided to properly put the MSM in place by increasing the frequencies of the spurious vibration modes to above the frequency range of interest, which should be determined on the basis of the frequency content of the ground input motion important to the SSI analysis.

Differential settlement and construction sequence considerations in foundation design

Bearing pressures imposed by a structural foundation on the surface of the underlying soil introduce stresses that cause the latter to deform, which ultimately leads to settlement of the foundation and the superstructure. Because soils are nonhomogeneous media and loads are not applied uniformly to the foundation footprint, the resulting settlements are not uniformly distributed. This means that certain areas of the foundation settle more or less than others; this is known as differential settlement. Differential settlement induces additional stresses on the foundation and superstructure that need to be evaluated and accounted for in the structural design. In addition, settlement does not occur instantaneously but is recognized as a time-dependent process. For certain types of soils (e.g., sandy soils), most of the settlement occurs during and shortly after construction because of soil compaction; however, for other types of soils (e.g., clayey or silty soils), settlement may continue for significantly longer periods of time because of soil consolidation. The structural design needs to account for these time-dependent effects.

The construction sequence also imposes additional stresses on the foundation and superstructure that are to a large extent dependent on the (short term) stiffness of the soil under the foundation. In particular, the construction process for pouring heavy foundation sections, such as those for a typical nuclear island (NI) basemat, needs to be carefully reviewed to ensure that differential settlements, particularly at softer soil sites, do not cause segmental cracking or any other distress to the structural system. For example, in past NPP designs, applicants have performed studies to identify limitations to the construction process to ensure that relatively uniform loads are applied over the foundation footprint. In light of these considerations, it is clear that the review of the effects of the construction sequence and (short-term) differential settlements should be performed concurrently because they are closely related.

From the point of view of a DC application, it is necessary to consider the following:

- How are the effects of the differential settlements accounted for in the standard design process, where assumptions need to be made about generic soil parameters?

- What specifications are established such that a COL applicant can demonstrate, for a particular construction sequence, that forces and moments induced by predicted and measured settlements at a particular site are bounded by those considered in the standard design?

It is emphasized that these issues are inherently site specific. Therefore, it can be challenging for a DC applicant to establish an interface that allows for the standard design to account for construction sequence and settlement loads. It can also be challenging to permit a COL applicant to verify that these loads are not exceeded during or after construction. To this end, additional enhancements were included in SRP Revision 4 to provide guidance to applicants about the interface issue. For DC applicants, the standard design should consider (1) a postulated set of soil stiffness parameters for the construction phase,

(2) a postulated set of soil stiffness parameters for the post construction phase, and (3) a postulated construction sequence and corresponding set of construction loads.

A COL applicant should perform a site-specific geotechnical investigation to determine predicted settlement profiles for construction and post-construction phases, based on the construction sequence to be used and the same methods as the DC application. If the predicted settlement profiles compare favorably to the DC settlement profiles—in terms of slope and curvature across the foundation footprint, not necessarily in absolute magnitude—then it is inferred that the forces and moments induced by the predicted settlements are bounded by the forces and moments considered in the standard design. In addition to the predictive calculations, a settlement monitoring program should to be established to verify whether measured settlements across the foundation footprint are consistent with predicted settlements during the operating life of the structure. The intent of the SRP enhancement is to have a COL applicant perform these verification activities as part of the interface considerations between the DC and COL applications.

Finally, the SRP enhancement includes general guidance about key issues to consider in the review of soil stiffness models used for the design of seismic Category I foundations, especially under static/gravity load conditions. It is indicated that soil stiffness can be represented by analytical or numerical (e.g., solid finite elements, distributed springs) formulations; however, it also is emphasized that that these formulations should be appropriate to the loading condition (seismic vs. gravity), soil type (granular vs. cohesive), foundation type and size (basemat, spread footing), and time scale of the loads (very short term seismic, short term construction, long term gravity) being considered.

Based on review experience with past DC and COL applications, structural design procedures typically utilize finite element models in which the foundation and superstructure are discretized with sufficient details. However, the soil is simplistically represented with distributed springs with stiffness parameters based on the subgrade modulus concept. Therefore, the review should focus on whether the stiffness of the distributed springs is appropriate to each analysis case. A certain spatial variation of stiffness may be required to capture dishing or Boussinesq effects when using distributed springs under static/gravity loads (stiffer at the edges and more flexible at the center of the basemat footprint). For seismic loads, on the other hand, it is difficult to use distributed springs to represent the overall dynamic foundation stiffness (which is frequency dependent and consists of independent vertical, horizontal, rotational and torsional components) in a manner consistent with the seismic SSI analysis. If distributed springs are used to represent dynamic soil stiffness under seismic conditions, especially for computing bearing pressures for foundation design purposes, then adequate technical justification needs to be provided.

The soil stiffness models used in structural design should be contrasted with those considered in geotechnical analysis codes (e.g., PLAXIS, FLAC, or SIGMA/W), which often incorporate relatively sophisticated constitutive models of the soil continuum but have only modest structural capabilities. The geotechnical settlement analysis used in the evaluation of differential settlement and construction sequence effects under SRP Section 3.8.5 is expected to be performed using such codes. However, it is not the intent of the SRP Section 3.8.5 enhancements to duplicate the settlement analysis reviewed under SRP Section 2.5.4. Based on past review experience, the latter review does not typically consider the coupling between the geotechnical and structural aspects that is essential to address foundation design issues. In particular, the iteration/feedback that would be necessary between the structural and geotechnical analyses as described in the SRP Section 3.8.5 enhancements would typically not be performed under SRP Section 2.5.4.

CONCLUSIONS

This paper provided a brief overview of key aspects of a recent NRC staff activity that has enhanced technical guidance based on the lessons learned from past application reviews. The enhancements focused on issues related to the seismic analysis and design of structures and foundations. Because of this effort, the staff has issued Revision 4 to SRP Sections 3.7 and 3.8. The staff also developed a companion rationale document to provide rationale and technical bases for incorporated enhancements. As these enhancements provide better clarity and additional guidance on complex technical issues, they will improve the effectiveness and efficiency in future application reviews.

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This work was performed under the auspices of the NRC. The findings and opinions expressed in this paper are those of the authors, and do not necessarily reflect the views of the NRC.

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