SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

LICENSING TOPICAL REPORT NEDO-33914, REVISION 1

BWRX-300 ADVANCED CIVIL CONSTRUCTION AND DESIGN APPROACH

GE-HITACHI NUCLEAR ENERGY AMERICAS, LLC

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1.0 INTRODUCTION

GE-Hitachi Nuclear Energy Americas, LLC (GEH), submitted Licensing Topical Report (LTR) NEDO–33914, Revision 0, “BWRX 300 Advanced Civil Construction and Design Approach,” dated January 20, 2021 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML21020A137), as supplemented by Revision 1 (ADAMS Accession No. ML21322A214) dated November 18, 2021. The U.S. Nuclear Regulatory Commission (NRC) staff reviewed the LTR with respect to the provisions proposed by GEH for the advanced civil construction of the BWRX-300 small modular reactor (SMR).

In response to the NRC staff’s requests for additional information (RAIs), GEH submitted letters dated August 19, 2021 (ADAMS Accession No. ML21231A255); September 13, 2021 (ADAMS Accession No. ML21256A008); and November 4, 2021 (ADAMS Accession No. ML21308A012). The NRC staff will evaluate the compliance of the final civil construction and design approach features for the BWRX-300 SMR during future licensing activities in accordance with Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, “Domestic Licensing Of Production And Utilization Facilities,” and/or Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants,” as applicable with the Limitations and Conditions (L&Cs) as outlined in Section 8.0 of this safety evaluation (SE).

1.1 Purpose

The purpose of the LTR is to provide guidelines for design, analysis, monitoring, and requirements for construction of a BWRX-300 SMR. The term “requirements,” as used in the LTR, as well as is used in this staff SE, is not associated with any specific NRC regulation or NRC requirement unless specifically identified as such in this SE. The term is instead used to describe what GEH has proposed to use for construction of a BWRX-300 SMR using innovative and comprehensive approaches that ensure safe operation throughout the life of the plant. GEH has referenced NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR [light-water reactor] Edition” (SRP), Chapter 2, “Site Characteristics and Site Parameters,” and Chapter 3, “Design of Structures, Components, Equipment, and Systems,” as they apply to aspects of its proposed construction criteria. Because these SRP sections may not apply directly to the proposed construction of an embedded reactor, the applicant supplemented the SRP guidance with associated guidance from NUREG/CR-7193, “Evaluations of NRC Seismic-Structural Regulations and Regulatory Guidance, and Simulation-Evaluation Tools for Applicability to Small Modular Reactors,” for the design of deeply embedded SMRs, as well as from associated industry standards and other guidance, as presented in its LTR and discussed in this SE. Specifically, the LTR describes the criteria, methodologies, recommendations, and approaches specific to the BWRX-300 SMR design and construction, as discussed in item A-Q of LTR Section 1.1.

Implementation

An applicant who references a topical report in a licensing application must demonstrate that the application of the topical report to their specific facility is within the scope of the conditions in the topical report defining its application. The staff verifies relevant criteria for accepted-for-use topical reports during each licensing action to ensure that the topical report's conclusions are both valid and applicable to the particular licensing action under review.

Accordingly, upon implementation of this LTR into a site-specific application of the BWRX-300 design, the staff will evaluate each topical area designated below to ensure that each topic appropriately interfaces with the proposed license application to ensure consistency. The staff will also make its regulatory determinations regarding the topics discussed below, as applicable, during its review of any future license application.

1.2 Scope

The scope of the LTR includes the following:

- The specific regulatory basis for each methodology described in this LTR for the analysis, design, and construction of the BWRX-300 SMR.
- Guidelines and requirements for characterizing subsurface conditions, including geotechnical site investigations and laboratory testing programs, as well as the inspection and monitoring programs performed during the excavation, construction, and operation of the BWRX-300 SMR.
- Requirements and guidelines for performing foundation interface analysis (FIA) to ensure the stability of both structure and the in situ soil and/or rock during and after construction.
- Design requirements, acceptance criteria and guidelines provided in the LTR for the analysis and design of the deeply embedded reactor building (RB), including the development of site-specific geotechnical and seismic design parameters.
- The BWRX-300 SMR approach for addressing the interactions between the seismic Category I (SC-I) RB and the surrounding structures and foundations (II/I interactions).
- Generic seismic and geotechnical design parameters that ensure the applicability of the BWRX-300 SMR generic design for a range of conditions present at the majority of potential North American candidate sites.

1.3 Description of the BWRX-300 SMR

LTR Section 1.3 provides high-level information about the BWRX-300 SMR and its proposed construction techniques. The BWRX-300 SMR is a water-cooled, natural circulation-driven SMR with a power output of about 300 megawatts electric. GEH has described how the BWRX-300 basis for design includes nine previous generations of the boiling-water reactor (BWR) and has evolved from the Economic Simplified Boiling-Water Reactor (ESBWR) Design Certification (DC), certified by the NRC in 2014 (10 CFR Part 52, Appendix E, "Design Certification Rule for the Economic Simplified Boiling-Water Reactor"). GEH has stated that the BWRX-300 incorporates design, analysis, and operating experience from the BWR operating fleet, advanced boiling-water reactor, and ESBWR, and adds evolutionary design improvements and new defense-in-depth design features and functions.

The BWRX-300 Reactor Pressure Vessel (RPV), Pressure Containment Vessel, and other important safety-related systems and components are located in the RB. The RB is placed in a vertical right-cylinder shaft and located below-grade to mitigate effects of possible external events, including aircraft crashes, adverse weather, flooding, fires, and earthquakes.

1.4 Reactor Building Below-Grade Shaft Construction

GEH proposes the open caisson technique as the preferred method to construct the RB shaft. A circular slurry shoring wall will be installed in the soil strata and socketed into the bedrock to stabilize the excavated shaft. The rock below the soil strata would be excavated to the bottom of basemat. Waterproofing material would be applied to the surface of the slurry wall and the rock face.

2.0 REGULATORY BASIS

In the LTR, GEH proposed innovative and comprehensive approaches to meet the NRC regulatory requirements of 10 CFR, Part 50, Appendix A, General Design Criteria (GDC). Specifically, requirements of GDC 1, “Quality standards and records,” and GDC 2, “Design bases for protection against natural phenomena.” Further, the construction approaches proposed by GEH in the LTR are established to meet the intent of NRC guidance, including the guidance prescribed in SRP Chapter 2 and SRP Chapter 3. Since there is no specific NRC guidance developed for embedded SMR reactors at this time, GEH used the guidance outlined in NUREG/CR–7193, as well as proposed construction requirements from industry standards.

LTR Section 2.0 provides statements of compliance with the regulations in 10 CFR Part 50 and 10 CFR Part 52, that GEH determined to be related to the civil construction and design of the BWRX-300 SMR. The LTR also identified design-specific information associated with relevant NRC guidance.

This LTR describes the intent to meet each of the relevant regulatory requirements for the BWRX-300 SMR. In some instances, the LTR indicates that specific design requirements for the BWRX-300 systems and components will be provided during future licensing activities.

The remainder of Section 2 describes each of the specific regulations that GEH addresses in this LTR. When the NRC receives an application for a BWRX-300 SMR, the staff will review the application against all applicable regulatory requirements related to the design and construction of the BWRX-300 SMR.

2.1 Regulatory Basis for Defining Site Subsurface Conditions

10 CFR Part 100

The regulations in 10 CFR Part 100 provide the reactor site criteria, including the physical characteristics, like seismology and geology, that shall be considered in siting a power reactor.

10 CFR 100.20(c)(1)

The regulation in 10 CFR 100.20(c)(1) points to 10 CFR 100.23. Part 100.20(c) requires that the Commission consider physical characteristics of the site.

10 CFR 100.23

The regulation in 10 CFR 100.23 sets forth the principal geologic and seismic considerations that guide the Commission in its evaluation of the suitability of a proposed site and adequacy of the design bases established in consideration of the geologic and seismic characteristics of the proposed site, such that, there is a reasonable assurance that a nuclear power plant can be constructed and operated at the proposed site without undue risk to the health and safety of the public.

2.2 Regulatory Basis for Development of Site Design Parameters

10 CFR Part 50, Appendix A, General Design Criteria 2

The regulation in 10 CFR Part 50, Appendix A, GDC 2 requires that nuclear power plant structures, systems, and components (SSCs) important to safety be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. This LTR describes a method for determining that a BWRX-300 SMR is designed to meet the requirements of GDC 2 for earthquake ground motions. The LTR focus on this hazard and does not discuss the other hazards in GDC 2, except for extreme winds, which is discussed in Section 6.3. As such, this SE does not discuss the other hazards.

10 CFR 100.23(d)(1)

10 CFR 100.23(d)(1) provides the requirements for defining the safe-shutdown earthquake (SSE) ground motion for a site and the need to address uncertainties in the site investigation and determination of site hazard.

2.3 Seismic Analysis Regulations

10 CFR Part 50, Appendix S, “Earthquake Engineering Criteria for Nuclear Power Plants,” requires that SSCs shall be designed to withstand the effects of the SSE ground motion or surface deformation are those necessary to assure: (1) the integrity of the reactor coolant pressure boundary; (2) the capability to shut down the reactor and maintain it in a safe-shutdown conditions; and (3) the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposures comparable to the guideline exposures of 10 CFR 50.34(a)(1).

2.4 II/I Interaction Guidance

SRP Section 3.7.2, “Seismic System Analysis,” Revision 4, December 2013 (ADAMS Accession No. ML13198A239), Subsection II.8 provides three interaction criteria for a non-seismic Category I structure to a SC-I structure (II/I interactions). Each non-seismic structure should meet at least one of these criteria:

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

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

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

These criteria ensure that collapse of a non-seismic Category I structure would be acceptable and no physical interaction between the non-seismic Category I and SC-I structures take place in a site SSE.

2.5 Testing, Inspection, and Monitoring Regulations

GDC 1 requires that structures important to safety be constructed and tested to quality standards commensurate with the importance of the safety functions to be performed. LTR Section 3 addresses the investigations, testing, inspections and monitoring programs proposed for the BWRX-300 SMR.

3.0 INVESTIGATIONS, TESTING, INSPECTION, AND MONITORING PROGRAMS

Since the BWRX-300 RB structure would be deeply embedded, additional site investigations, laboratory testing, and field monitoring programs would be needed in addition to inspections during construction. Changes in in situ stress distribution in the subgrade materials during excavation and construction can induce movement in the surrounding soil and rock media.

GEH states that the suitability of a particular site would be verified through an extensive site investigation program. The laboratory and field testing programs would include both soil and rock properties including the properties of different interfaces. Parameters needed to model the interfaces are shown in LTR Figure 4-2 (also discussed in response to NRC RAI 02.05.04-01 dated November 4, 2021). A site monitoring program would monitor the conditions within the RB shaft and its surrounding media. Movements of the subgrade materials and change in groundwater would be particularly monitored due to their influence on the stability of the RB shaft. Necessary field instrumentation will be deployed to measure such changes. Additionally, the observations in the field monitoring program would be used to calibrate the FIA model discussed in LTR Section 4.0.

The staff notes that the scope of field investigations, laboratory and field testing, and field monitoring programs may be more than in a conventional LWR because the BWRX-300 SMR RB will be deeply embedded. In addition, GEH proposes to calibrate the FIA model with the observations made at the site. This calibration program, as discussed in the LTR and evaluated by the staff below, is acceptable to the staff.

3.1 Site Investigation and Subsurface Material Testing Programs

An extensive site investigation and testing of subsurface materials would ascertain whether a particular site is suitable for deploying the BWRX-300 SMR. A significant portion of the RB structure is deeply embedded in the subgrade materials, which may be comprised of soil, rock, or both. The interaction of the reactor structure with surrounding soil/rock media is important for the integrity of the RB structure and its response under both static and dynamic loads. Change in the in situ stress field during excavation, construction, and operation of the BWRX-300 SMR may induce movement in the surrounding medium.

The site investigation and testing programs of the subsurface materials should be able to determine the necessary parameters of all models that would predict the response of the RB shaft and its surrounding media. GEH has developed the site investigation and field and laboratory testing programs following Regulatory Guide (RG) 1.132, “Geologic and Geotechnical Site Characterization Investigations for Nuclear Power Plants,” Revision 3, October 2021 (ADAMS Accession No. ML21298A054) and RG 1.138, “Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants,” Revision 3, December 2014 (ADAMS Accession No. ML14289A600). In addition, the technical bases described in RG 1.132 are provided in Appendices A and B of NUREG/CR–5738, “Field Investigations for Foundations of Nuclear Power Facilities,” November 1999 (ADAMS Accession No. ML003726925).

GEH states that it adheres to the guidance in NUREG/CR–5738 to develop the site characterization program for the BWRX-300 SMR. However, because the BWRX-300 SMR includes a deeply embedded RB, the site investigation and subsurface materials testing program would go beyond the current regulatory guidance of RG 1.132, RG 1.138, and NUREG/CR–5738.

The staff finds the approach GEH has presented is reasonable. The site investigation and programs for field and laboratory testing programs are developed following the current regulatory guidance and are supplemented by additional programs, as discussed further below, because the BWRX-300 SMR includes a deeply embedded RB structure.

The staff also notes that the site investigation program and the associated laboratory and site testing programs are somewhat dependent on the site and reactor design. The staff will perform a detailed evaluation to confirm that the final design features and associated analyses would satisfy the regulatory requirements of GDC 2 when the agency receives a license application for construction and or design of a BWRX-300 SMR.

3.1.1 Site Investigation Program

Figure 3-1 of the LTR shows a preliminary layout of the BWRX-300 SMR single unit plant and preliminary borehole locations for geotechnical and geophysical investigations for a typical site. Expected type and number of tests are given in Table 3-1. The LTR states in Section 3.1.1, that a minimum of 21 borings are anticipated for a BWRX-300 SMR installation, more than the recommended number of borings in Appendix D of RG 1.132 to ensure adequate characterization of the subsurface properties surrounding the RB structure. GEH has set the maximum required depth of these boreholes at approximately 120 m based on the change in in situ vertical stress.

The staff agrees that more boreholes compared to typical conventional nuclear plants will be necessary to characterize the surrounding media for BWRX-300 SMR because it is deeply embedded. However, the spatial variation of the subsurface characteristics and material properties greatly influence the minimum number of boreholes necessary for adequate characterization of the surrounding media. Because of the site-specific nature, the staff cannot make a determination at this time regarding the adequacy of the number of boreholes which would be necessary and the appropriateness of their specific locations with respect to the RB shaft. In addition, the actual dimensions of the RB and the in situ stress field would dictate whether 120 m would be adequate for the maximum depth of the boreholes. Therefore, the staff also cannot determine whether the maximum depth of the borehole equal to 120 m would be adequate for every site. The number of boreholes and maximum depth are site-specific design requirements that will need to be provided during future licensing activities.

Additionally, GEH has stated, in LTR Section 3.1.1, a geological mapping program would map the rock fracture network in the same geological units exposed at nearby outcrops and in boreholes. In this context, the rock fractures include the geological discontinuities, such as rock joints, bedding planes, faults, zones of weakness, etc. The geological mapping program would characterize the rock mass with associated fractures for assessing stability of the surrounding media, development of the rock mass parameters, and guiding the field investigation and development of the FIA model, as discussed in LTR Section 4.0.

In response to NRC RAI 02.05.04-02, dated November 4, 2021, GEH has stated that it may construct additional inclined borings to intersect the geological discontinuities at better orientations and additional borings to investigate subsurface structural features (e.g., the fracture network) if the results from fracture mapping indicate the need. Data obtained from the borings would supplement the fracture network mapping leading to a better characterization of the rock mass. Surface geophysical measurements will also be used to better mapping of the subsurface features in between the borings. The borings will also provide recovered cores, televiewer measurements, seismic measurements, access for water pressure tests in bedrock, and allow installation of piezometers.

The staff agrees that the additional rock fracture network and the information from the rock fracture mapping can be used to assess the stability of the embedded shaft under both static and seismic loads. The staff also finds that the discussion on the rock fracture mapping program is consistent with Appendix B, “Geologic Mapping of Tunnels and Shafts,” of NUREG/CR–5738 and is, therefore, reasonable.

3.1.2 Laboratory Testing Program

The LTR lists the types of tests that will be conducted at a minimum in the laboratory on samples of soil and rock collected at the site to determine the required parameters needed in subsequent analysis, as described in LTR Section 4 and Section 5. GEH will perform a sufficient number of laboratory tests to minimize uncertainties in the geotechnical input properties of each soil and rock type. The estimated parameter values will be provided in terms of its mean and standard deviation. Estimates of systematic bias (epistemic uncertainty) and measurement bias (aleatory uncertainty) will be developed for the measured parameters.

In addition, GEH will conduct direct shear, triaxial strength, and other appropriate tests to estimate the strength and deformation properties of different types of interfaces, as discussed in LTR Section 4.0 and in response to NRC RAI 02.05.04-1, dated November 4, 2021. These interfaces include the interface between the RB structure and the surrounding rock/soil medium and interfaces between two geologic media (e.g., rock-rock interface for rock fractures, bedding planes, etc., and rock-soil interface). This testing program of an interface will determine the necessary parameters for the rheological model of an interface, as illustrated in LTR Figure 4-2. In response to NRC RAI 02.05.04-2 dated November 4, 2021, GEH has stated that large diameter samples containing the natural discontinuities present in the subsurface of a site would be used to determine the interface properties of the rock fractures using direct shear or triaxial tests (see LTR Section 3.1.3). GEH may also conduct other laboratory tests, such as expansion, creep, erodibility, and durability, as needed, to characterize the subsurface materials.

The staff finds that the lists of laboratory tests for soil and rock properties are reasonable because these tests are typically performed in soil and rock engineering projects. In addition, the staff finds that the tests identified to determine strength and deformation parameters of different interfaces are appropriate and have been used in other industries, such as mining and construction industries. Strength and deformation properties of the interface between the RB structure and the surrounding medium are very important as they influence the response of the RB structure during an SSE. Characterizing the uncertainties associated with this and other interfaces will provide confidence in modeling the response of the RB structure and surrounding media, for example, in the FIA discussed in Section 4 of the LTR.

As discussed in LTR Section 4.3.4.3, the FIA modeling will use two sets of values for each of the elastic and/or inelastic properties measured during the loading and the unloading phases for both soil and rock media. Therefore, the staff expects to review material property values for both loading and unloading phases in a site-specific license application.

In addition, the staff will perform a detailed evaluation to confirm that the final design features and associated analyses would satisfy the regulatory requirements of GDC 2. The staff review will also include an assessment to determine if any other tests would be needed for a site-specific application for the BWRX-300 SMR. During any future license application review, the staff would verify whether all appropriate tests have been conducted to determine all the parameters necessary to design and construct the BWRX-300 SMR with an embedded RB at any designated site. Also, the staff would assess the plants structural safety performance for a site-specific SSE. A limitation and condition (L&C) # 1 for this testing program is described in Section 8.0 of this SE.

3.1.3 Characterization of Rock Mass Properties

GEH has proposed to use the empirical geomechanical rock mass classification systems, namely, Rock Mass Rating (RMR) system (Bieniawski, Z.T., “Rock Mechanics Design in Mining and Tunneling,” A.A. Balkema, 1984), and Geologic Strength Index (GSI) system (Hoek, E., and E.T. Brown, “The Hoek–Brown failure criterion and GSI – 2018 edition,” Journal of Rock Mechanics and Geotechnical Engineering, 11(3), pp. 445–463, 2019), to estimate the rock mass properties. These classification systems have several geologic and engineering parameters which are determined through rock fracture mapping at the site and laboratory testing. The staff notes that these rock mass classification systems are extensively used in mining, construction, and tunneling projects in a wide variety of rock masses. Therefore, the staff accepts these systems as reasonable to classify rock mass at a site selected to deploy a BWRX-300 SMR.

GEH has also stated that the presence of cavities would be identified during subsurface investigations of the site. The spacing and depth of investigation would be adjusted to detect the anticipated features, consistent with RG 1.132. The staff accepts the approach proposed by GEH as it is reasonable and generally practiced in industry.

3.2 Construction Inspection and Testing Program

3.2.1 Excavation and Foundation Inspections and Testing

GEH has proposed to conduct excavation and foundation inspections to satisfy the geotechnical and foundation inspection procedures contained in U.S. NRC, Inspection Procedure (IP) 88131, "Geotechnical/Foundation Activities," 2006 (ADAMS Accession No. ML060530176). Key site parameters would be verified through the average allowable static bearing capacity and maximum allowable dynamic bearing capacity for normal plus SSE loading. The staff considers the approach to verify key site parameters through inspections and testing of foundations as reasonable because they are consistent with the NRC inspection procedures.

3.2.2 Building Structure Construction Inspections and Testing

GEH has stated that the construction inspection and testing program would cover the project phases from the start of the shaft sinking through the BWRX-300 SMR construction and plant commissioning. GEH states that the construction inspection and testing program would satisfy the structural concrete inspection procedures of the U.S. NRC, IP 88132, "Structural Concrete Activities," 2006 (ADAMS Accession No. ML060530186) and structural welding inspection procedures of the U.S. NRC, IP 55100, "Structural Welding General Inspection Procedure," 1983 (ADAMS Accession No. ML061660235). The inspection program would include visual inspection of the accessible concrete surfaces and determination of susceptibility of concrete to deterioration. The staff concludes that GEH's proposed construction inspection and testing program is consistent with the procedures of the NRC IPs 88132 and 55100. In addition, the staff determines that the program also follows the guidance of the national standard, such as American Concrete Institute (ACI) 349.3R, "Evaluation of Existing Nuclear Safety-Related Concrete Structures," 2002 (Reapproved 2010) and American Society of Mechanical Engineers (ASME), Boiler and Pressure Vessel Code, Section XI "Rules for Inservice Inspection of Nuclear Power Plant Components," New York, NY, 2013.

3.2.2.1 Concrete Compressive Strength Testing Frequency

GEH has proposed a compressive strength testing program of safety-related concrete samples during construction. The in-process concrete strength would be tested in accordance with Section 5.6.2.1 of ACI 349-13, "Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary," 2014, following the guidance in RG 1.142, "Safety-Related Concrete Structures for Nuclear Power Plants (Other than Reactor Vessels and Containments)," Revision 3, May 2020 (ADAMS Accession No. ML20141L613). GEH has proposed additional sampling frequency requirements to ensure a statistically significant sample size. The staff finds the proposed approach to concrete strength testing to be reasonable because it is consistent with NRC guidance. Moreover, the proposed approach follows the national standard ACI 349–13, as suggested in RG 1.142. Additional sample testing to develop a statistically significant sample size is also reasonable. The staff notes that during the review of future licensing applications, the staff will audit the in-process concrete strength tests.

3.3 In-Service Monitoring Program

3.3.1 Scope of Structures Monitoring and Aging Management Program

The Structures Monitoring and Aging Management Program (SMAMP) of the BWRX-300 SMR would monitor the in-service conditions of the structures to detect any degradation and deformation to ensure that credited safety functions as well as overall structural integrity are maintained throughout their design lives. This structural monitoring program begins after commissioning of the plant and continues until completion of plant decommissioning. The SMAMP of BWRX-300 SMR also includes below-grade structural members and foundations including monitoring of settlement and differential settlement. This SMAMP program, as evaluated by the staff in Section 3.3.2 of the SE, is reasonable. The staff notes that during the review of future licensing applications, the staff will audit the SMAMP and its implementation.

3.3.2 Framework of Structures Monitoring and Aging Management Program

The LTR has described the framework of the BWRX-300 SMAMP, which is based on the three-tier evaluation hierarchy given in ACI 349.3R, "Evaluation of Existing Nuclear Safety-Related Concrete Structures," 2002 (Reapproved 2010). The three-tier evaluation is shown schematically in LTR Figure 3-2. Following the guidance in ACI 349.3R, the LTR states that the inspection interval is defined in SMAMP and the personnel conducting the inspection shall be qualified as per Chapter 7, Qualification of Evaluation Team, of ACI 349.3R.

The LTR states that structural evaluation would follow the logic tree as shown in LTR Figure 3-2. The SMAMP has three tiers. In Tier 1, structures would be evaluated against qualitative and quantitative thresholds for visual inspections or condition surveys (First tier criteria) following Section 5.1 of ACI 349.3R. If a structure fails in Tier 1 evaluation, it would be subjected to Tier 2 evaluation. In Tier 2, structures would be evaluated against qualitative and quantitative thresholds for observed degradation in accordance with Section 5.2 of ACI 349.3R. Observed conditions failing the Tier 2 criteria would be evaluated to a Tier 3 evaluation. In Tier 3, structures would be evaluated using more enhanced methods to assess the structural condition. This evaluation would follow Section 5.3 of ACI 349.3R. Any corrective actions needed for a structure would follow the guidance given in Chapter 8, Repair, of ACI 349.3R. Provisions of the SMAMP would also include periodic sampling and testing of groundwater to assess whether the below-grade structures are exposed to an aggressive environment. If necessary, addition site-specific criteria would be developed.

The staff finds from the description of the SMAMP in the LTR that it would be designed following the national standard ACI 349.3R, and therefore the design of the program is reasonable. The definitions of the three tiers of evaluation follows ACI 349.3R. The logic tree for evaluation, as shown in Figure 3-2 of the LTR, is from Figure 5.1 of ACI 349.3R. The personnel conducting the evaluations shall be trained as per Chapter 7 of ACI 349.3R. Any remedial action needed would be in accordance with ACI 349.3R. The staff also finds that this section of the LTR is consistent with the provisions given in the latest version of ACI 349.3R, "Report on Evaluation and Repair of Existing Nuclear Safety-Related Concrete Structures," 2018. Based on the above, the staff finds that the description of the BWRX-300 SMAMP is reasonable as it is based on a recognized standard.

3.4 Field Instrumentation Plan

The LTR states that field instrumentation would be used to monitor the magnitude, spatial, and temporal distributions of the deformation and displacements of the media surrounding the deeply embedded BWRX-300 RB structure. In addition, distribution of the pore pressure would also be monitored using the field instrumentation. Short-term and long-term settlement monitoring plans are developed to measure both vertical and horizontal displacements in and around the structures. Differential distortion across the footprint of the foundations of the control building (CB), turbine building (TB), radwaste building (RwB), and RB, as well as the differential settlement between any two structures, would be monitored. Locations of the sensors would depend on the areas anticipated to have a large response. Where practical, sensors would be connected to datalogger(s) for periodic measurements.

The site monitoring program of the subsurface materials surrounding the RB structure should be able to detect and quantify any changes or movements in the surrounding media so that appropriate actions can be taken at each stage of the life of the reactor. The staff finds this generic description of the field instrumentation plan to be reasonable as it has provisions to detect any deleterious movement of the media surrounding the reactor system. Any deleterious movement of the surrounding media would need rehabilitation to restore the stability. It should be noted that a field instrumentation plan should be both site-specific and design-specific. Therefore, the staff will review the instrumentation plan with details of the instrumentation to be deployed considering a specific site and details of the reactor design when the agency receives a site-specific application for the BWRX-300 SMR.

4.0 FOUNDATION INTERFACE ANALYSIS

In this section, the LTR discusses the FIA. The purpose of the FIA model is to ensure that the BWRX-300 RB, CB, TB, and RwB structures and the surrounding soil and/or rock remain stable throughout the life of the plant and meet the guidance in SRP Section 2.5.4, “Stability of Subsurface Materials and Foundations,” Revision 5, July 2014 (ADAMS Accession No. ML13311B744). The FIA will be conducted at different life stages of the BWRX-300 SMR to assess the construction plans, possible ground improvements, excavation support, and foundation interface design. The predicted foundation interface behavior would be compared with the actual observations made in the field monitoring program, as discussed in Subsection 3.4 of this LTR. Additionally, the results of the FIA would be used to verify the RB shaft design, as discussed in LTR Section 5.1.3.

LTR Section 3.4 provides the verification of the FIA results with the measured field observations. The field instrumentation approach, as described in Section 3.4, is used for monitoring and evaluating possible instabilities of the subgrade materials during the excavation, construction, and operation of BWRX-300 SMR. Together with the results of FIA, as described in Section 4.3.4, this approach is beyond the current guidance of SRP Section 2.5.4.

4.1 Foundation Interface Analysis Model

The FIA is a three-dimensional numerical model that examines the response of the BWRX-300 SMR’s structures and its surrounding media from change of in situ subgrade conditions at each life stage: excavation, construction, loading, and operation of the reactor. The numerical model will be calibrated with the measured response at the site at each life stage.

The FIA model has the capability to incorporate nonlinear stress-strain response of the soil and rock media, the interface to simulate slippage along and opening across an interface, limited structural systems, soil/rock support systems, and fluid-soil/rock interaction. An interface could be between the RB shaft and surrounding media (rock/soil), faults, rock joints, etc. The model has the capability to analyze the interaction of the BWRX-300 SMR RB structure and the surrounding media at different life stages of the RB structure.

The staff finds the description of the FIA numerical model to be reasonable because the description gives an overall picture of what the FIA model is intended to accomplish in addition to how the model results would be calibrated.

4.2 Subgrade Material Constitutive Models

The LTR states that the constitutive models of the BWRX-300 FIA would be based on characteristics of the site-specific data obtained from the field and laboratory testing programs, as described in LTR Section 3.1. Measurement results from the field instrumentation, described in LTR Section 3.4, would be used to modify the input parameters of the selected models. The staff finds this approach to be reasonable as it is generally used in the industry.

4.2.1 Soil Constitutive Models

GEH expects that a nonlinear constitutive model would be appropriate to represents the stress-strain relationship of the soils to be encountered at a site. GEH has proposed to use the bilinear Mohr-Coulomb model for representing the soil behavior. This model exhibits linear, elastic deformation with increasing stress up to the failure. Beyond failure, the stress-strain behavior is represented by a fully plastic model. Other more sophisticated constitutive relationships, e.g., strain-hardening or strain-softening models, may be used if the soil(s) at the site show(s) the need. The staff finds the discussion of selecting a particular constitutive model for representing the stress-strain behavior of site-specific soil(s) to be reasonable as it is generally used in the industry. The staff notes that during the review of future licensing applications, the staff will review the selected constitutive model to represent the soil response under load and the associated parameters.

4.2.2 Rock Constitutive Models

Rock mass may contain several types of fractures or discontinuities: rock joints, faults, bedding planes, etc. These fractures may make the rock mass an assemblage of complex-shaped blocks. In addition, the discontinuities are generally significantly weaker than the rock matrix (intact rock blocks) and mostly control the rock mass behavior. Response of a fractured rock mass may become complex from interaction among compression, translation, rotation, and potential generation of new or opening of existing fractures. The LTR mentions two constitutive models to represent the stress-strain response of the fractures rock mass: Mohr-Coulomb model and Generalized Hoek-Brown (GHB) 2018 model. The shear strength of a rock mass, represented as a Mohr-Coulomb material, are developed from the results of field investigation and laboratory tests, discussed before. The GHB model uses the uniaxial compressive strength of the intact rock and the GSI geomechanical classification scheme of the rock mass to estimate the rock mass strength and deformation parameters.

The staff notes that both Mohr-Coulomb and GHB models are commonly used in rock engineering applications. The staff agrees with GEH that GHB model may be more suited to represent a fractured rock mass as it has been developed specifically for that purpose incorporating the rock fracture network information of the rock mass through the GSI index value. The staff notes that during the review of future licensing applications, the staff will review the model selected to represent the response of a rock mass under load and determination of the model parameters.

4.3 Non-Linear Foundation Interface Analysis Approach

In this LTR Section, GEH highlighted the sections where the interface modeling, structural modeling, and fluid-soil interaction in the FIA model at different life stages of the BWRX-300 SMR (siting, excavation, and construction) are discussed. Interface modeling includes the contact between the structure and the surrounding soil and/or rock media, and the contact between two sides of natural fractures or discontinuities, such as bedding planes, rock joints, fault planes, that are present in the rock mass.

4.3.1 Interface Models

4.3.1.1 Interface Between the Structures and the Subgrade Media

The LTR describes the response of the interface between the structure and the surrounding soil and/or rock media. The response of the interface or the contact plane between the structure and the subgrade media significantly affects the pressure exerted by the soil or rock medium on the structure. During a seismic event, the response of the structure with respect to the surrounding media would be controlled by the response of the wall interfaces. In comparison, the response of the interface at the base may not be that critical for the RB as deep embedment will likely control the sliding and overturning.

The LTR has provided the interface rheological model typically used with the BWRX-300 SMR in LTR Figure 4-2. Two sets of springs, one along and another across the interface, between two opposing sides of an interface are used as the interface element in the numerical model. The slippages along and opening/closing across the interface are controlled by these two springs. A series of these spring couplers would model the response of the entire interface. The relative sliding (shear) response of each spring along the interface is controlled by its stiffness. The LTR is proposing to use the elastoplastic Mohr-Coulomb criterion to model the shear behavior along the interface. The dilation/contraction or opening/closing of the interface is controlled by the normal stiffness of the spring and will be modeled using a tensile strength cut-off of the spring.

GEH has proposed that the parameters of the interface model, as shown in Figure 4-2 of the LTR, would be determined from the laboratory tests discussed in LTR Section 3.1.2. The LTR has also mentioned use of information collected in LTR Section 3.1.3, Characterization of Rock Mass Properties, to determine the interface parameters of the interface between the structure and the surrounding media. GEH, in response to the NRC Question 02.05.04-01, states that direct shear and/or triaxial test would be performed on rock discontinuity samples to estimate the interface properties.

In addition, GEH, in LTR Section 4.3.1.1 and in response to RAI 02.05.04-01, has stated that the development of the interface parameters should be consistent with the limitations and modeling guidance of the software used in the FIA. The staff finds the overall approach presented to estimate the parameters of the rheological model of the interface between the structure and the surrounding media by measuring it in laboratory experiments to be reasonable because it is commonly used in the industry. The staff notes that during the review of future licensing applications, the staff will review the interface model (Figure 4-2) parameters determined from the samples collected during site investigation. The staff notes, however, that if the laboratory-measured parameter values are outside the bounds of the selected software, then the software is not appropriate for the FIA modeling purpose for the scenario.

4.3.1.2 Fault or Joint Planes or Interfaces Between Bedding Units in a Geologic Formation

Faults, joints, or bedding planes are geological discontinuities of the rock mass. Response of these discontinuities in rock mass surrounding the BWRX-300 SMR's structures are analyzed throughout the life stages of the facility. GEH proposes to model these discontinuities using the approach discussed in LTR Section 4.3.1.1, Interfaces Between the Structures and the Subgrade Media. The parameters of the rheological model of a geological discontinuity, as shown in LTR Figure 4-2, will be determined through laboratory tests. Specifically, direct shear test and/or triaxial tests are conducted on recovered rock cores with natural discontinuities from field investigation, as discussed in response to RAI Question 02.05.04-01. Additionally, if properties of specific discontinuities are required, samples of these discontinuities would be collected in the field for testing in the laboratory. In response to RAI Question 02.05.04-01, GEH is also proposing to conduct laboratory tests on artificial surfaces. It is not clear how artificially created interfaces can be substituted instead of natural discontinuities because the roughness structure of both types of surfaces can be fundamentally different. The staff will review in a future site-specific application the rationale of using artificially created interfaces to determine the parameters of natural rock discontinuities.

Additionally, GEH proposes to use the weakest strength parameters of the interface elements out of the results from strength tests conducted on multiple discontinuities. The interface would have reduced strength after some displacement (slip). Strength reduction from the peak strength may be accomplished using strength reduction factors to estimate these residual strength parameters. In the response to RAI Question 02.05.04-01, GEH proposes to use the minimum parameter values representing the residual state of the discontinuities present in the rock mass.

The staff agrees with GEH that to model the natural discontinuities using the rheological model shown in LTR Figure 4-2 is reasonable because this rheological model has been used in numerous projects around the world and is commonly used in the mining and construction industries. The staff finds the proposal to estimate the model parameters from laboratory testing of samples of natural discontinuities, collected during field investigation at the site, reasonable as the parameters would be measured directly from samples containing actual discontinuities. The staff also agrees that the residual strength parameters of a natural discontinuity after small slippage would be smaller than the peak values. Strength reduction from the peak state to the residual state of the natural discontinuities is appropriate; however, the staff concludes that the minimum peak values of a set of discontinuities represent the peak value of the weakest discontinuity. The staff notes that in future licensing applications, the staff will review the parameters of the rheological model (Figure 4-2) of natural discontinuities from the laboratory tests. This review will address, as discussed above, the following items: (1) reduction of peak shear strength to residual shear strength of a discontinuity and (2) the minimum peak shear strength that is the shear strength of the weakest discontinuity in the discontinuity set.

4.3.2 Structural Elements Representation in the Foundation Interface Analysis Model

The LTR states that the FIA model of the BWRX-300 SMR will include representations of the RB structure and soil stabilization elements, such as liners, stabilization walls, rock anchors, etc. They will be represented as linear elastic materials in the model to capture the interaction between the structure and the subsurface materials because the surrounding materials will fail long before the onset of structural failure. Only elastic response is assumed to determine whether deformations or stresses in any structural member reach levels beyond the intent of the design. GEH also states that the model of the RB structure would be sufficiently refined to adequately capture the interaction with the surrounding media and transfer the loads to and from the media.

The staff finds that the use of linear elastic materials properties of the RB structure and stabilization elements is reasonable because the surrounding media would undergo plastic and large deformation before the structural members show onset of inelastic behavior. Additionally, the staff finds the use of only elastic properties is reasonable to identify structural members experiencing undesirable levels of stresses or deformations.

4.3.3 Fluid-Soil Interaction

GEH proposes to measure the elevation of the groundwater table and hydraulic properties of the subsurface materials during site investigation. The FIA model may include a hydraulic interface to simulate the effects of groundwater on the structure during the life stages of the BWRX-300 SMR structures. The model would be capable of simulating both short-term and long-term effects of dewatering.

The staff notes that the proposed approach only considers matrix flow of the groundwater. Depending on the fracture network in the rock layers and level of groundwater at the site, groundwater may flow into the excavation through selected discrete fractures (fracture flow). The staff also notes that occurrence of fracture flow is site dependent and will conduct an appropriate review as part of a site-specific license application for construction and or design of a BWRX-300 SMR. Additionally, the staff notes that the proposed model is not capable of simulating any deleterious effects from a corrosive environment that the presence of water may introduce.

4.3.4 Analysis Staging Approach

GEH states that the FIA is conducted at different life stages of the BWRX-300 SMR structures to determine the stress and deformation at different points of interest in the numerical model of the structures and the surrounding media.

4.3.4.1 Site Characterization

The FIA model at the site characterization stage of the BWRX-300 SMR system would simulate the initial in situ stress field. This stress field will be aligned with the initial baseline displacement field. The staff notes that GEH has stated that the initial stresses will include the measured horizontal stresses and any influence of the groundwater, if applicable. The staff agrees with the approach as this is commonly used in modeling an excavation. The staff also notes that the initial stress field should include vertical and horizontal stresses, the vertical stress at a site is generally from the gravity driven load. In response to NRC RAI Question 02.05.04-08, dated November 4, 2021, GEH clarifies that the in situ stress field (vertical and two horizontal stresses) will be measured at the site.

4.3.4.2 Excavation

During excavation of the shaft to place the RB structure, tensile stress may develop in the surrounding media due to redistribution of the initial stresses. The change in in situ conditions will be modeled in the FIA model during excavation of the shaft. The progression of excavation will be simulated by removing layers of soil or rock within the shaft in the FIA model. Stability of the shaft as the excavation progresses will be verified by comparing the FIA results with the actual field observations.

The staff finds the proposed modeling scheme during the excavation stage described in the LTR to be reasonable as it is typically followed in modeling excavations in soil/rock medium. Comparing model results with the actual observations will allow calibration of the FIA model parameters as the excavation progresses.

4.3.4.3 Construction

Construction of the reactor adds additional loads to the surrounding media. GEH would use in the FIA model loading elastic and/or inelastic properties of soil and rock in place of unloading properties used in analyses of the Site Characterization (Section 4.3.4.1) and the Excavation (LTR Section 4.3.4.2) stages. GEH proposes to compare the field observations from the field monitoring (Section 3.4) and construction inspection (Section 3.2). Effects of any soil movement or displacement along joints will be continually analyzed to assess stability of the structure, foundation, and surrounding media.

The staff finds that the modeling approach during the reactor construction stage is reasonable because it is typically followed in the industry. Comparing the model results with field observations and construction inspection would further calibrate the FIA model. In addition, effects of any actions can be easily investigated before implementation.

4.3.4.4 Loading

Construction of civil structures and foundations, in addition to placement of mechanical and electrical components, introduces permanent dead loads to the reactor system and the surrounding media. Other loads, such as weight of the fuel, water in the pools, cranes, and other permanent loads would be introduced in the FIA model at this stage. In addition, loads from the foundations of the CB, TB, and RwB structures would also be introduced in the model at this stage together with the loads from any backfill materials. Comparison of the FIA results with the observations from monitoring will continue at this stage.

The staff finds that the approach described at this loading stage is reasonable as it is typically followed in the industry. Comparison with the monitored observations during the phases of construction and operation would be expected for the BWRX-300 SMR (LTR Figure 4.8).

4.3.4.5 Start-Up and Operation

During the operational life, the BWRX-300 SMR may experience additional loads from seismic ground motion, floods, and any potential subsurface instability. The FIA model would be used to assess the potential effects of these additional loads on the environment of the reactor. In addition, GEH proposes to use the FIA model to assess the response in between points monitored by the field instrumentation.

The staff finds the proposed approach is reasonable because it is typically used in the industry. In addition, use of the modeling results to assess the response at points without any actual observations is also common industry practice and would be expected for the BWRX-300 SMR construction and operation.

5.0 DESIGN ANALYSIS

5.1 One-Step Design Analysis Approach

In LTR Section 5.1, GEH presents the overall approach to the analysis of the RB under the effects of the imposed static and dynamic loads, which includes:

1. Self-inertia loads including loads from equipment and pool water,
2. The mass and impedance of the surrounding in situ subgrade materials,
3. Groundwater hydrostatic pressure; and
4. Overburden loads and the interaction with the surrounding RwB, CB, and TB foundations and structures.

In this one-step approach, GEH proposes to implement the process laid out in Section 3.1.2 of American Society of Civil Engineers/Structural Engineering Institute (ASCE/SEI) 4-16, "Seismic Analysis of Safety-Related Nuclear Structures and Commentary," 2017, for the design of the BWRX-300 RB structure. Static and dynamic structural stress demands are obtained directly from the results of the soil-structure-interaction (SSI) analyses of combined models that include the finite element (FE) representations of the RB structure and the surrounding medium. The surrounding subgrade is represented by a layered half-space continuum with equivalent linear elastic stiffness properties and complex damping.

Stress demands on the members of the RB structure due to static earth pressure, structural self-weight, equipment weight, and live loads are calculated by applying 1g gravity loads on the combined model of the RB structure and the subgrade continuum. The structural demands due to overburden pressures from the nearby foundations are also calculated by the 1g static analysis. Additional static analyses are performed to calculate the structural demands due to hydrostatic wall pressures from the pool water, and normal operating and accidental pressure loads. Separate analyses provide the structural demands due to normal operating and accidental pressure and thermal loads. Structural demands due to seismic inertia loads and dynamic soil/rock pressure loads are obtained from the seismic SSI analyses, described in LTR Section 5.3.

The methodology used for development of RB FE model is based on the methodology described in LTR Section 5.1.1 and the SSI modeling assumptions presented in LTR Section 5.1.2. Equivalent linear properties are used as input for the static and seismic SSI analyses developed as described in LTR Sections 5.2.1 and 5.2.4, respectively. LTR Section 5.1.3 presents the unique BWRX-300 SMR approach used to demonstrate that the linear elastic SSI analyses provide soil and rock pressure load demands with sufficient design load margins to address the modeling uncertainties.

The staff finds that the overall approach to compute the design demands of the RB is reasonable because GEH has committed to the use of consensus practices of ASCE 4 and other static analysis methods.

5.1.1 FE Model of RB Structure

The staff has reviewed the modeling approach of the RB structure, presented in LTR Section 5.1.1, which states that the structural FE model will consist of beam, shell, solid, and spring elements representing the RB structural configuration for all main structural members including shear walls. The FE model includes gross discontinuities such as large openings and member eccentricities. Rigid beams or rigid links are proposed for modeling member eccentricities and offsets. Linear elastic contact springs connect the RB structural and subgrade FE models. Stiffness properties, which are assigned to the contact springs, represent the interaction mechanism between the structure, the water proofing material, and the soil/rock.

The LTR states that the mesh of the FE models will be sufficiently refined to produce stress demand calculations that are not significantly affected by a further refinement of the FE size or shape. Finer meshes will be used around penetrations and openings that are larger than half of the wall or slab thickness. Meshes of major walls and slabs to consists of at least four shell elements along the short direction and at least six shell elements along the long direction.

The FE models used for seismic SSI analyses will be sufficiently refined mesh to transmit the entire frequency range of interest for the seismic design of the RB SSCs, in accordance with ASCE/SEI 4-16, Section 5.3.4. The LTR states that the material properties of the concrete structural elements would be based on ACI 349-13 and of steel or steel-plated composite (SC) members of the RB and would be based on American National Standards Institute (ANSI)/American Institute of Steel Construction (AISC) N690-18," Specification for Safety-Related Steel Structures for Nuclear Facilities," 2018, respectively.

The staff finds the LTR approach to modeling the RB structure reasonable because such modeling practices have been used in other nuclear installations and have provided acceptable results.

5.1.2 Soil-Structure Interaction Modeling Assumptions

In LTR Section 5.1.2, GEH presents the approach to assigning the stiffness properties established using the approaches discussed in LTR Sections 5.2.1.1 and 5.2.1.2. The contact springs represent the interface between the structure, the waterproofing material, and the surrounding soil/rock mass. The LTR states the upper bound stiffness properties are assigned to the contact springs normal to the RB exterior walls. Contact springs in the vertical and tangential direction are assigned very low stiffness values to simulate the effect of zero friction between the wall and subsurface in the respective directions.

The soil and rock strata in the SSI models use isotropic linear elastic properties and are used to compute the design demand for the RB structure. Potential discontinuities or cavities in the rock mass are not explicitly included the SSI models. The LTR has made simplifying assumptions to support the above approach: (1) the properties of the subgrade materials are linear elastic (small strain), (2) nonlinearities at the soil/rock interfaces with the structures are neglected, (3) the rock mass is continuous free of any discontinuities, and (4) the static lateral pressures on the RB shaft due to the weight of self-supporting rock can be neglected. Assessment of the potential effects of waterproofing materials and RB shaft construction have been discussed in LTR Section 5.3.8.

The staff finds the assumptions made for assigning the upper-bound stiffness in the normal direction and a low value of stiffness in the vertical and tangential directions to the springs at the interface of the RB and the surrounding media to be reasonable because they are consistent with current practice used in SSI analysis.

The design of the BWRX-300 SMR inherently assumes a self-supporting or stable rock mass surrounding the RB shaft, as indicated in this section of the LTR. GEH, in response to RAI 02.05.04-05 and 02.05.04-06, states that a stable shaft excavation would have no unstable blocks in its surrounding that may slide into the excavation or potentially unstable blocks would be stabilized by reinforcement. A self-supported (even with some temporary reinforcement) excavation would be needed to place the RB and to estimate the earth pressure loads to be considered in the generic design of the RB structure. GEH does not consider a rock mass stable over the life of the BWRX-300 SMR if it requires permanent supports (reinforcement), as stated in response to NRC Question 02.05.04-06. As discussed in its response, the "BWRX-300 SMR can be deployed at soil sites and sites having rock masses that require support during the excavation and construction of the deeply embedded" RB shaft. GEH stated that "The as-built site-specific subgrade conditions must ensure the stability of the BWRX-300 SMR power block foundations." Although small yielding is expected even in a self-supported rock mass, the yielding should not induce earth pressure exceeding the RB design limit. GEH proposes to identify fractures zones, joints, bedding planes, discontinuities, and other zones of weakness at a site through characterization of the rock fracture network (response to RAI 02.05.04-02) to analyze stability of rock mass surrounding the RB shaft.

GEH proposes to estimate the earth pressure on the RB shaft from unstable rock blocks in the surrounding rock mass using the FIA that includes rock-rock discontinuities with appropriate properties (LTR Section 4.3.1.2 and response to RAI 02.05.04-01 and 02.05.04-05) and/or force-equilibrium analysis. The staff notes that the force-equilibrium method implicitly assumes rigid blocks. As such, the rationale for GEH's assumption that rigid blocks would be appropriate is a site-specific design requirement that will need to be provided during future licensing activities.

The primary focus in estimating the earth pressure will be to include all unstable blocks so that the estimated earth pressure will include contribution from all unstable blocks and will be bounding (response to NRC Question 02.05.04-05). If the subsurface conditions at the site result in large loads to the RB shaft, the BWRX-300 SMR may still be sited with additional mitigating measures, such as over-excavating and backfilling, to reduce the load on the RB shaft.

Based on the above discussion, the staff finds that assumption of a stable rock mass surrounding the RB shaft is reasonable. The staff will make its final conclusions on the methods used to identify unstable blocks in the surrounding rock mass and the mitigation measures to be taken to stabilize them during any future site-specific license review of the BWRX-300 SMR. A L&C # 2 is described in Section 8.0 of this SE.

5.1.3 Design Earth Pressure Load Validation

In LTR Section 5.1.3, GEH proposes to compare the estimated soil and rock pressure loads on the exterior walls of the RB structure using the results of the nonlinear FIA analysis and the linear elastic 1g design analysis to assess: (1) the effects of nonlinear and possibly anisotropic subgrade response on the soil and rock pressures, and (2) the conservatism of the soil and rock pressure loads to design the RB structure from the 1g analysis, as described in LTR Section 5.1.2. Only unimproved soil and rock conditions would be considered due to uncertain longevity of any ground improvements made at the construction stage. The rock pressure on the RB shaft wall may be uniform because of contact grouting. Alternatively, it can be concentrated loads if rock blocks are reinforced to stabilize the surrounding rock mass. GEH has assumed that the excavation is stable with the initial (or, temporary) rock support. In addition, the liner would be able to withstand the entire rock load as the rock support systems placed initially would degrade over time. Additional load may come from presence of hydrostatic head and swelling of the rock. In addition, loads from other surface structures may be transferred to potentially unstable rock blocks and, thereby, impart at least a fraction of the load on the RB structure.

The staff finds that GEH has proposed a reasonable approach to develop an estimate of the earth pressure comprising of soil and/rock pressure by comparing the results from the FIA model and 1g design analysis because this approach is commonly used in the nuclear industry.

The distribution of the lateral pressure with depth at the site obtained from the FIA model is compared with that from the 1g design analysis to establish the load margins. If the calculated soil and rock design load margins are below a threshold established to adequately address the uncertainties and variabilities of subgrade properties, GEH would adjust the linear soil and rock stiffness properties used in 1g design analysis.

In addition, for sites in high seismic regions, if the FIA results indicate that nonlinearity of geometry and material properties introduces significant anisotropic effect on estimating the rock and soil pressures, GEH proposes to conduct sensitivity analyses of the nonlinear SSI model. The sensitivity analyses are expected to assess the effects of nonlinear soil and rock response in developing the demand of dynamic lateral pressure.

The staff finds that GEH has presented a reasonable approach to estimate the lateral loads at a site. Comparing the results from the FIA model with the 1g linear model is expected to develop a set of material properties that would bound the results from the FIA model. In cases with high seismicity and/or highly nonlinear subgrade materials, GEH would conduct sensitivity analyses to assess the effects of nonlinearity and high seismicity. The staff notes that during the review of future licensing applications, the staff will review the computed lateral earth pressure loads on the exterior wall of the RB structure as well as the need for nonlinear SSI analysis.

5.1.4 Probabilistic Earth Pressure Analyses

GEH has proposed to perform probabilistic assessment of the earth pressure used to design the deeply embedded RB shaft. The probability density function of the subgrade pressure would be computed at the discrete regions of the external wall of the RB structure in contact with soil or rock medium. The objective of this assessment would be to demonstrate that the magnitude of earth pressures used would adequately bound the uncertainties in calculating the earth pressure loads. Two types of uncertainties would be addressed: (1) epistemic or uncertainties associated with the models used to estimate the earth pressure, and (2) aleatory or uncertainties of the parameters posed by natural randomness and uncertainties in measuring the properties of the subgrade materials.

The staff finds that GEH has presented a reasonable approach to characterize uncertainties associated with the measured parameters and models for estimating the earth pressure, as reviewed below. Use of the probability density function of the subgrade pressure is the standard approach in statistical analysis to characterize the types of uncertainties.

5.1.4.1 First Order Second Moment Method

GEH has proposed use of the First Order Second Moment (FOSM) method to estimate the probability density function of the ground pressure. The mean and variance of the earth pressure are calculated using the simplified models in LTR Section 5.1.4.3 or from the results of the FIA model, discussed in LTR Section 4. The derivatives of the earth pressure with each parameter are calculated for each discretized region.

The staff finds that GEH has presented a reasonable approach to use the FOSM method to calculate the mean and variance of the earth pressure at the discretized region as this method is widely used in probabilistic analysis. The staff also notes, as GEH has described in this section, that the FOSM method is appropriate if the relationship between the ground response and the geotechnical parameters are generally linear. For highly nonlinear cases, higher order formulations or the Monte Carlo method (discussed in LTR Section 5.1.4.2) would be appropriate to use.

5.1.4.2 Monte Carlo Method

GEH has proposed to use the Monte Carlo method as an alternative to the FOSM method to address the uncertainty associated with the probability distribution of the earth pressure. A minimum of 60 random realizations would be generated of each parameter whose variation has important effects on the earth pressure. These generated parameters are then used to calculate the earth pressure including its distribution.

The staff finds that GEH has reasonably selected the Monte Carlo method to assess the variation of the estimated earth pressure. The Monte Carlo method is widely used to propagate the uncertainties in the parameters if input uncertainties are represented as distributions, as discussed above and in NUREG/CR–2300, “A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants,” Volumes 1 and 2, 1983 (ADAMS Accession No. ML063560439 and ML063560440), Section 12.4.3.1.2, Monte Carlo Simulation. Additionally, the Monte Carlo method is also useful if the relationship between the parameters and the response is highly nonlinear.

5.1.4.3 Probabilistic Analysis Earth Pressure Models

In this section, GEH has discussed methods to estimate the variation of earth pressure accounting for variation of individual parameters. Each parameter, whose variation has a significant effect on the estimated earth pressure, is related to the earth pressure in each discretized region through: (1) an analytical model, (2) a force-equilibrium model, or (3) a FE or a finite difference model. Analytical models give the distribution of earth pressure calculated using the individual distributions of subgrade material properties. Force-equilibrium models may be used to assess stability of individual rock blocks by analyzing the potential to slide along the discontinuities.

The staff notes that GEH has presented three alternative methods to estimate the variation of the earth pressure due to variation of individual parameters. All these methods are commonly used depending on the scenario to be analyzed. The staff also notes that although the force-equilibrium method, as shown in LTR Figure 5-1 for a sliding wedge, can be used to estimate the probability of sliding given the distribution representing each parameter, the method implicitly assumes rigid blocks. Stresses and strains cannot develop in these blocks. In contrast, both the FIA model (discussed in LTR Section 4) and the design analyses (discussed in LTR Section 5) deal with deformable blocks as the blocks generate stresses and strains.

5.1.4.4 Combining Discrete Probability Distributions

GEH has discussed the approach to develop a continuous earth pressure distribution by combining different discrete distributions. GEH proposes to use the Monte Carlo method for combining these discrete parameter distributions with their degree of belief for a particular outcome. GEH wants to determine the belief probabilities using "a lottery or a probability wheel."

The staff finds that GEH has presented a reasonable approach to combine different occurrence distributions into a continuous combined distribution of the final outcome or parameter (e.g., estimated earth pressure). This approach is typically used in probabilistic analysis. GEH also proposes to use the degree of belief to assign the probability that the results for each random realization would belong to a particular process or model. This is a reasonable approach; however, the staff notes that during the review of a site-specific license application, the staff will audit the values of the degree of belief have been determined.

5.2 <u>Site-Specific Geotechnical and Seismic Design Parameters</u>

GEH describes their approach to develop the equivalent linear properties of the soil and/or rock masses surrounding the RB shaft used in static SSI analysis in LTR Section 5.2.1. Approaches proposed to develop the magnitude and frequency content of the site-specific design ground motion spectra are discussed in LTR Section 5.2.2. Probabilistic site response analyses (SRA) to be conducted to incorporate the effects of overlying materials with appropriate epistemic uncertainties and aleatory variabilities are also discussed in Section 5.2.2.

Five sets of ground motion time histories compatible with the ground motion design spectra have been generated and described in Section 5.2.3. Results of these SRAs would be used to develop the stiffness and damping properties of the subgrade materials, as discussed in LTR Section 5.2.4.

5.2.1 Equivalent Linear Subgrade Static Properties

The LTR Section 5.2.1 presents, in broad terms, the approach taken to quantify:

1. The static earth pressure demands on the below-grade exterior walls are obtained using a 1g static analysis of the three-dimensional (3-D) RB FE model embedded in a layered half-space continuum model representing the surrounding soil and rock. The approach utilizes the effective weight, elastic modulus and Poisson's ratio of the soil/rock. For a soil layer, the Poisson's ratio is representative of the at-rest lateral pressure condition.

2. The design demands due to groundwater pressures is considered in a separate FE analysis where hydrostatic pressures are applied to the below-grade walls at elevations below the nominal groundwater level.

The LTR also states that the profiles of the equivalent linear subgrade properties for use as input to the static analysis of the BWRX-300 SMR RB are correlated with the results of nonlinear soil/rock stability analysis to ensure that the design envelopes all uncertainties related to nonlinear behavior of soil and rock mass.

The staff finds the approach to establish the static earth pressure demand on the exterior wall of the RB to be reasonable because the results from the approaches are used to establish the equivalent linear subgrade static properties. The determination of subgrade material properties is further discussed in the LTR Sections 3.2, 4.0, 5.1.2, 5.1.3, 5.2.1, and 5.2.4.

5.2.1.1 Equivalent Linear Stiffness Properties of Soil Materials

LTR Section 5.2.1.1 proposes the approach to define the stiffness properties of the subsurface materials, represented by the Young's modulus E_{st} using the effective unit weight γ and Poisson's ratio υ_{st} of the soil half-space. The LTR also proposes different correlations that can be used to convert results from field tests, such as cone penetration tests, standardized penetration tests, pressure meter tests, and dilatometer tests, in conjunction with the laboratory testing of undisturbed samples under triaxial unconsolidated undrained compression, or triaxial consolidated undrained compression to estimate the E_{st} values. The LTR, in addition, suggests the use of field measurement of shear wave velocities V_s to estimate the E_{st}. The LTR proposes the estimation of a lower bound (LB) E_{st} using methods that impose small strain in the subsurface soils. LB E_{st} values are obtained based on the weighted log-mean and log-standard deviation of the measured values using appropriate weight factors reflecting the level of confidence on the data from different field and laboratory tests.

The staff finds the approach presented is reasonable because multiple field methods and test procedures (as standardized by the American Society for Testing and Materials) are used in the different correlations which reduces the bias from the use of a single type of field or laboratory data using a statistical approach for establishing the mean and the LB estimate.

UB values for soil effective unit weight are calculated as mean plus one standard deviation of the measured values from the site investigation and laboratory tests. The staff finds this as a reasonable approach to address uncertainties in soil unit weight measurements.

The staff agrees that the value of υ_{st} can be determined from the coefficient of lateral pressure at-rest K_0, as stated in the LTR. Although LTR Section 5.2.1.1 does not specifically discuss how GEH proposes to estimate the strain-dependent modulus reduction and other dynamic properties of the soil (and also rock) following SRP Section 2.5.4, Stability of Subsurface Materials and Foundations, LTR Section 7.3, uses generic curves from Electric Power Research Institute (EPRI)-102293: "Guidelines for Determining Design Basis Ground Motions," 1993. In addition, LTR Section 3.1.2, lists several dynamic tests to estimate the strain-dependent modulus reduction and hysteretic damping properties of soil and rock (e.g., Resonant Column Torsional Shear, cyclic triaxial, Free-Free Resonant Column velocity test, etc.) at a site. The staff notes that during the review of a site-specific license application, the staff will audit these tests and approach(es) used to estimate the dynamic properties of soil (and also rock).

5.2.1.2 Rock Mass Equivalent Linear Properties

GEH has proposed several different empirical approaches using both GSI and RMR classification systems to estimate the equivalent properties of a rock mass. The GSI-based empirical approach, proposed by Hoek, E., and M.S. Diederichs, "Empirical estimation of rock mass modulus," International Journal of Rock Mechanics and Mining Science, Vol. 43, No. 2, pp 203–215, 2006, is one of the proposed approaches that use the intact rock modulus E_{ri} and the degree of rock disturbance from the excavation process D to estimate the rock mass modulus E_{st}. D varies from 0 for undisturbed confined rock to 1 for blast damaged rock. As noted by Hoek and Diederichs, measured value of the intact rock modulus E_{ri} from undisturbed specimen is seldom available. Development of microcracks from stress relaxation can severely damage the samples. The intact rock modulus can be reduced by approximately 50 percent by these microcracks compared to undamaged samples and in situ determination of the modulus by the geophysical methods.

GEH has proposed to use the empirical equation, given by Hoek and Diederichs, to estimate intact rock modulus E_{ri} from the uniaxial compressive strength measurements using the modulus ratio values. Hoek and Diederichs give the modulus ratio, which is generally a range, for different types of rock. GEH has also proposed to use the Simplified Hoek and Diederichs empirical model, given by Hoek and Diederichs, if reliable estimation of the intact rock modulus E_{ri} cannot be made.

GEH has also proposed to use three RMR-based empirical approaches to estimate the rock mass modulus E_{st}. One of these empirical approaches is from Galera, J.M., M. Álvarez, and Z.T. Bieniawski, "Evaluation of the deformation modulus of rock masses using RMR: Comparison with dilatometer tests," Proceedings of the11th International Society of Rock Mechanics Congress, Workshop W1, Taylor & Francis, 2007, which correlates the rock mass modulus with the intact rock modulus and the RMR rating of the rock mass. GEH has also proposed to use another RMR-based approach, given Serafim, J.L. and J.P. Pereira, "Considerations of the geomechanics classification of Bieniawski," Proceedings of International Symposium Engineering Geology and Underground Construction, September. Lisbon (Portugal); 1983. p. II–33–42, for rock masses with the RMR rating of less than 50 (very poor to somewhat poor rock mass). In addition, GEH has also proposed an approach for rock masses with the RMR rating greater than or equal to 50 (fair to very good rock) by Bieniawski Z.T. "Determining rock mass deformability-experience from case histories." International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstract, 15(5): 237–47, 1978.

The staff notes that all these proposed rock mass classification-based approaches are widely used in projects around the world. The staff also notes that the approaches using the intact rock mass modulus E_{ri} in combination with the rock mass classification rating values (e.g., Hoek and Diederichs, Galera, Alvarez, and Bieniawski) are relatively recent and based on a significant years of field experience combined with measured values. As noted by Hoek and Diederichs, the Simplified Hoek and Diederichs method, as given in LTR Equation (5-20), gives larger scatter of the estimated rock mass modulus E_{st} than the equation using the intact rock modulus E_{ri}. Both RMR-based approaches, given by Serafim J.L. and J.P. Pereira, "Considerations of the geomechanics classification of Bieniawski," Proceedings of International Symposium Engineering Geology and Underground Construction, September. Lisbon (Portugal); 1983. p. II-33–42 and Bieniawski (1978), do not cover the entire range of the RMR rating values (0 to 100). In summary, based on the preceding discussion, the staff finds that the empirical approaches proposed by GEH to estimate the rock mass modulus E_{st} are reasonable; however, care should be taken for applying any of these methods to ascertain that all the conditions of its use are satisfied at the given site. In addition, the staff notes from Hoek and Diederichs that the classification schemes assume isotropic and homogeneous rock mass. This implies that a rock mass must contain a sufficient number of discontinuity sets so that its deformational behavior can be considered as isotropic. As such, a L&C # 3 has been described in Section 8.0 of this SE.

The LTR also mentions that the equivalent linear rock stiffness properties may be adjusted based on the results of the FIA model. It is not clear to the staff why these equivalent linear rock stiffness (modulus) values need any adjustment and what would be the basis to adjust them using the FIA results. The staff will review the rationale for such adjustment in a future site-specific licensing case.

Based on the above discussion, the staff finds that GEH has proposed several alternative approaches to estimate the equivalent linear rock stiffness properties. These approaches may have some limitations based on the data sets used to develop them, as discussed above. The staff finds all these approaches are reasonable as they are used in many different mining and construction projects around the world. The staff notes that during the review of a site-specific license application, the staff will audit the estimated equivalent rock stiffness properties.

5.2.2 Development of Site-Specific Ground Motion Spectra

The LTR Section 5.2.2 states that the development of the site-specific SSE ground motion for the seismic design of SC-I SSCs should utilize a site-specific probabilistic seismic hazard analysis (PSHA) using models relevant to the site selected. Using guidance in RG 1.208, “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion,” Revision 0, March 2007 (ADAMS Accession No. ML070310619) and SRP Section 3.7.1, “Seismic Design Parameters,” 2014 (ADAMS Accession No. ML14198A460), applicants referencing the LTR should develop a site-specific GMRS. In addition, applicants referencing the LTR should calculate the foundation input response spectra (FIRS), performance based intermediate response spectra (PBIRS), and performance based surface response spectra (PBSRS) using appropriate transfer functions developed by performing a site response analysis. The final response spectra are the result of the base rock or reference PSHA results convolved with a site-specific site response calculation performed using Approach 3 as defined in NUREG/CR–6728, “Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-consistent Ground Motion Spectra Guidelines,” October 2001 (ADAMS Accession No. ML013100232). The LTR states that the site response calculation should be performed using two types of variability in the dynamic material properties underlying the site: (1) the aleatory variability of the site should be modeled to account for random variations in material properties within the site boundary, and (2) the epistemic uncertainty should be accounted for by multiple base-case profiles. These base-case profiles and parameters that determine the amount of aleatory variability should be determined based on the at-site geotechnical investigations.

The LTR states that in order to estimate the vertical spectrum, applicants should use the vertical/horizontal (V/H) ratios provided in NUREG/CR–6728 or in recent scientific publications on the topic. Because different spectra are calculated for different purposes (e.g., the GMRS, which defines the free-field motion at a competent surface versus the FIRS, which defines the seismic demand at the foundation level), different V/H ratios may be appropriate for different response spectra.

The LTR also states that, in accordance with 10 CFR Part 50, Appendix S, the site-specific seismic hazard results must exceed the five-percent damped spectra defined by RG 1.60, “Design Response Spectra for Seismic Design of Nuclear Power Plants,” Revision 2, July 2014, (ADAMS Accession No. ML13210A432) anchored at 0.1g. This ensures that the site-specific aspects of the BWRX-300 SMR structures seismic design complies with the minimum SSE of 0.1g, as defined in Appendix S to 10 CFR Part 50.

The staff finds that GEH’s requirements for the development of a site-specific SSE and supporting response spectra follows the current NRC guidance for meeting 10 CFR Part 50,

Appendix S and 10 CFR 100.23(d) for the determination of the site-specific seismic hazard. However, because the seismic hazard is site-specific, the staff notes that it will perform a detailed evaluation and make its final conclusions on seismic hazards during any future site-specific license review of the BWRX-300 SMR.

5.2.3 Development of Ground Motion Acceleration Time Histories

LTR Section 5.2.3 outlines an approach for developing ground motion acceleration-time histories for input in SSI analyses. The approach outlined in LTR Section 5.2.3 follows the approach described in SRP Section 3.7.1, and DC/COL–ISG–01, “Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in DC and Combined License Applications,” NRC, May 2008 (ADAMS Accession No. ML081400293).

The staff finds that the approach for developing the acceleration-time histories is acceptable because relevant NRC guidance and acceptance criteria in the SRP are used to determine the development and applicability of the acceleration-time histories.

5.2.4 Strain Compatible Subgrade Dynamic Properties

In LTR Section 5.2.4, GEH presents the methodology for establishing the strain-compatible dynamic soil column properties for the deterministic SSI analysis using ASCE/SEI 4-16, Section 5.1.4. To address the uncertainties related to the determination and variation of subgrade conditions, a set of three seismic SSI analyses are performed using the Best Estimate (BE), LB, and UB subgrade profiles reflecting the as-built site conditions of the site. Section 5.1.7(c) of ASCE/SEI 4-16, guidance recommends that the properties used as input to the SSI analyses be consistent with the soil properties used in the generation of input motion. The soil profiles used in the probabilistic SRA described in Section 5.2.2 of the LTR are used for development of the SSI analysis profiles of strain-compatible dynamic subgrade properties, which are consistent with the probabilistically based design motions. The effects of primary nonlinearity of the subgrade materials response are addressed by using an equivalent linear representation of dynamic stiffness and damping properties compatible to the free-field strains induced by an SSE.

The staff finds the approach to develop the soil profiles for the SSI analysis is reasonable as it maintains the consistency of the seismic motion developed in the SRA and captures the uncertainty associated with the variability of the soil properties across the site. The staff finds assurance in the fact that this practice has been used in previous license applications and has produced reasonable results.

In addition, the LTR provides a new approach to develop the Hazard Consistent Strain-Compatible Properties (HCSCP). This new approach assumes strain-compatible properties are approximately log-normally distributed, consistent with observed strong ground motion parameters (NRC, 2001) and makes use of the distributions of strain-compatible properties cataloged during development of the suites of amplification factors. The staff finds the approach to estimate the strain-compatible dynamic properties of the subgrade materials presented in this section of the LTR to be reasonable, but the staff does not have the assurance of past regulatory practice with this approach. The staff, therefore, concludes that if this first-of-a-kind approach is applied in a site-specific application using the BWRX-300 SMR structures, the staff will audit the HCSCP approach in that application. A L&C # 4 is described in Section 8.0 of this SE.

5.3 Reactor Building Seismic Soil-Structure Interaction Analysis

Section 5.3 of the LTR states that the seismic demand of the RB is computed using the SSI code SASSI (a system for analyses of soil-structure interaction) following the analytical procedure described in Section 5 of ASCE/SEI 4-16. Linear elastic SASSI analyses are performed for the set of frequencies selected in LTR Section 5.3.2. The superposition principle, applicable to linear elastic analyses, allows the SASSI stress results obtained from dynamic and static analyses of different subproblems to be combined with the results of static analyses in seismic design load combinations and used in member design. The three deterministic SSI analyses use the strain-compatible soil columns developed using the same approach and data from the SRA along with the acceleration-time histories described in Section 5.2.3 of the LTR. The effects of non-vertically propagating shear waves on the seismic response and design of RB SSCs are addressed as described in LTR Section 5.3.3.

Although the effects of ground motion incoherency are generally neglected in the design of BWRX-300 SMR, these effects may be included in the design in hard rock high frequency sites by using the coherency functions specified in Section 2.0 of DC/COL–ISG–01 or other coherency functions adequate for the site-specific conditions. In the design, ground motion incoherency effects are included after considering the comparisons of the coherent and incoherent responses and demands, and consideration of the potential variation of the coherency function with depth.

Additionally, sensitivity of the SSI analyses is considered to address the uncertainties related to the effects of excavation support and fill concrete, described in Section 5.3.8 of the LTR; the soil separation, discussed in Section 5.3.9 of the LTR; and variation of groundwater level, as discussed in Section 5.3.10 of the LTR. If these effects produce responses significantly higher (>10%) than the design-basis analyses, the results of the sensitivity analysis would be incorporated in the seismic design of the BWRX-300 SMR to bound these uncertainties.

In the LTR, GEH has proposed the SASSI extended subtraction method (ESM) simplification as an alternate approach to calculate the SSI system impedance matrix. In this method, only a selected set of nodes of the excavated volume are specified as the interaction nodes. These interaction nodes are established in the ESM model at: (1) the interfaces between the excavated volume and structural models, (2) the top surface of the excavated volume located at the PBSRS elevation, and (3) planes within the excavated volume located at PBIRS elevations. GEH proposes to use additional interaction nodes in layers of softer soil material to improve the accuracy of the SSI solution. The accuracy of the solutions obtained from the ESM analyses would be demonstrated following the guidelines provided in SRP Section 3.7.2.

GEH proposes to validate the ESM results by analyzing reduced (quarter or half)-size models. These models will be analyzed using the ESM and the SASSI flexible volume or direct method (DM) with all nodes of the excavated volume specified as interaction nodes.

If the site is located in a high seismic region and the results of the nonlinear static FIA, described in Section 4.0, indicate that the nonlinear response of the subgrade materials is significant, seismic SSI analyses will be performed using the nonlinear SSI models described in LTR Section 5.3.11 to assess the sensitivity of the RB seismic response and design on the nonlinear effects.

The staff finds the approaches to include the SSI effects in the seismic design of the BWRX-300 SMR to be reasonable. The approaches described to include the effects of ground motion incoherency, the sensitivity of excavation materials, groundwater elevation changes, and soil separation in the SSI analysis are aligned with accepted practice. The staff finds assurance in the fact that the methods proposed are well accepted methods and have been used in the past to yield acceptable results. Use of nonlinear analysis in SSI assessment is not a common approach in licensing of the nuclear power plants; however, the staff will rely heavily on the information that is provided in a future site-specific license review of the BWRX-300 SMR to characterize and model the nonlinear behavior. A L&C # 5 has been provided in Section 8.0 of this SE.

5.3.1 Key Seismic Responses

The LTR proposes the use of key nodal locations to compare the response at these locations from the variation of the SSI parameters in the analysis. The key locations will be selected using the following criteria:

- Nodes at intersections of main structural members (main structural walls) at ground and other major floor elevations to capture global responses.
- At least two roof nodes, one central and one corner node, to show all important modes of seismic response of structure including the effects of rocking and torsion.
- At least two basement nodes, one central and one corner node, to show the SSI effects on the translational as well as the rotational (rocking and torsion) responses of the foundation.
- For the below-grade portion of the RB structure, cross-sections subjected to high seismic stress demands.

The approach of using key response locations and locations of high stress demands to compare the effect of the variation in SSI parameters is reasonable because these are important locations for assessing the effects of variation of SSI parameters on the design of the RB structure.

5.3.2 Frequencies of Analysis

The solution for the response of the SSI system will be obtained over a selected set of frequency points and then interpolated for other frequency points. The analysis is performed up to a cut-off frequency value established based on the largest value required following the four criteria of ASCE/SEI 4-16, Section 5.3.5(b). The highest dominant frequency is determined for each SSI analysis based on the acceleration transfer function representing the in-structure responses at the selected key locations, described in Section 5.3.1 of the LTR. The cut-off frequency determined by the criterion will be used in the analysis using the stiffest subgrade profile and the UB structural stiffness properties.

For lower values of the cut-off frequency, the analyses use softer subgrade profiles with reduced structural stiffness properties. In such cases, GEH commits in the LTR to demonstrate that the analysis of the stiffest profile provides responses that are bounding for frequencies higher than the cut-off frequencies used for the analyses with the softer subgrade profiles by comparing transfer function and 5 percent damped in-structure response spectra (ISRS) at the key locations selected within the structure. The frequencies of analysis are conducted at sufficiently small frequency intervals. Transfer function amplitude calculated at the key locations will be inspected to detect any numerical anomalies in the interpolated transfer functions (e.g., sharp narrow spikes) that can potentially affect the accuracy of the results. If any numerical anomalies are present, GEH commits to evaluate the effects of these anomalies in the interpolated transfer function using analysis at additional frequencies to ensure that the anomalies in the transfer function interpolations do not affect the accuracy of the calculated responses.

The staff finds that these approaches are reasonable because they have been used in prior licensing applications and are well documented in industry consensus documents. Due to previous experience with this approach, the staff has reasonable assurance that the approach, when utilized, will yield acceptable results.

5.3.3 Effects of Non-Vertically Propagating Seismic Waves

The LTR Section 5.3.3 proposes use of sensitivity evaluations to address the effect on the SSI analysis from non-vertically propagating seismic waves for the BWRX-300 SMR design, a significant portion of which is embedded in the subsurface. Non-vertically propagating seismic waves may result in different site response and SSI results than would be expected using vertically propagating waves. No specific approach has been identified but it is suggested in the LTR that the effects of 2-D or 3-D wave propagation are to be addressed which may result from site characteristics like dipping bedrock surfaces, dipping subgrade layers, topographic effects, and other impedance boundaries, as well as the effects of local seismic sources generating inclined waves. The LTR states that if significant multi-dimensional effects are anticipated, a site-specific sensitivity analysis is performed to confirm the conclusions of the 1-D analysis.

The NRC staff finds that the approach is acceptable as it explicitly accounts for the site-specific nature of the site response analysis and the potential for multi-dimensional site effects at highly variable sites.

5.3.3.1 Evaluations of Multidimensional Wave Propagation Effects

The LTR proposes to use 1-D wave propagation analysis for rock and soil layer dipping less than the limits presented in NUREG/CR–0693, “Seismic Input and Soil Structure Interaction,” February 1979. Multidimensional, 2-D or 3-D, wave propagation sensitivity analyses may be required to study the potential generation of inclined seismic waves when site characteristics significantly deviate from the basic assumption of infinite horizontal layers. These deterministic sensitivity SRAs are typically to be performed on two models with the same subgrade material properties and configuration as the BE base-case profiles used for the 1-D SRAs described in Section 5.2.2 of the LTR. Two sets of deterministic SRAs would be performed on models representing:

1. The base-case profile used for the probabilistic SRA that assumes idealized site conditions with infinite horizontal layers, and

2. The actual site characteristics including dipping bedrock surfaces, dipping subgrade layers, topographic effects, and impedance boundaries.

Control motions may be applied to these SRA models at the bedrock surface elevations where the site reference seismic hazard is defined. The amplitude and frequency content of the input control motions are selected based on the PSHA results for rock-based Uniform Hazard

Response Spectra (UHRS) with the exceedance frequencies of 10^{-4} and 10^{-5} per year. For the sites where the nonlinearity of the subgrade materials can have a significant effect on the site response, equivalent linear sensitivity SRA would be performed using two or more UHRS controlling earthquakes with energy contents that dominate appropriate frequency ranges. For example, two control motions may be used as representative of a high frequency earthquake that dominates at high frequency range (5 and 10 Hz) and a low frequency earthquake that dominates at low frequency range (1 and 2.5 Hz). Acceleration-time histories or the Random Vibration Theory control motions may be used that match the spectral shapes generated from the reference site UHRS.

Site amplification factors are calculated based on the 5 percent damped Acceleration Response Spectra results of each deterministic SRA for the site response at the FIRS, PBSRS, and PBIRS elevations. Comparisons are made of the amplification results obtained from the SRA of model representing 1-D and multi-dimensional site conditions to determine if the site characteristics increase, decrease, or produce similar site response results. Based on these comparisons, the FIRS, PBIRS, and PBSRS, developed based on the results of 1-D probabilistic SRA analyses as described in Section 5.2.2 of the LTR, may be increased.

The staff finds this approach to addressing dipping layers in the subsurface reasonable because the effect of wave propagation due to dipping layers will be addressed in the seismic demand, when needed.

5.3.3.2 Evaluation of Local Seismic Source Effects

The presence of a local seismic source may also generate inclined waves due to the potential source-to-site effects on the wavefield. Generally, the angle of incidence of the seismic waves decreases as the waves propagate towards the ground surface due to Snell's law. Thus, non-uniform sites with softer soil layers create a vertical velocity gradient and the effects of inclined waves are reduced due to this decrease of the angle of incidence. NUREG/CR–6728 indicates rock sites at distances from the source of about 10 to 15 km or less show inclined shear wave motions. Substantial inclined shear wave motions are not shown for rock and soil sites at distances of more than 15 km from the source. Therefore, for these sites, the local seismic source effects on the BWRX-300 SMR seismic design can be neglected.

To address the inclined seismic sources that may influence the SSI analysis, the LTR proposes to use the guidance in NUREG/CR–6896, "Assessment of Seismic Analysis Methodologies for Deeply Embedded Nuclear Power Plant Structures," February 2006 (ADAMS Accession No. ML060820521) that SH waves, representing the horizontal component of the inclined shear waves, have little effect on the SSI response at the basemat level while the SV waves, representing the vertical component, influence the peak vertical response. Therefore, the LTR has not considered the effect of SH on the seismic demand for design of the BWRX-300 SMR. NUREG/CR–6896 further establishes that the effect of the SV waves is maximum when the angle of incidence is near the critical angle of incidence $\emptyset_{cr}$. GEH proposes to evaluate the effects of the inclined shear waves on the design of the BWRX-300 RB by considering SV waves at two different inclination angles $\emptyset_{cr}/2$ and $\emptyset_{cr}$ using a two-step approach. Effects of the inclined SV waves on the free-field response as well as on the FIRS, PBSRS, and PBIRS will be assessed using a free-field model without any structure in the first step. If the results indicate significant effects (>10%) of the inclined SV waves, then the SSI model of the BWRX-300 RB is evaluated with inclined SV waves.

The staff concludes that a reasonable approach has been presented in this section of the LTR for addressing the effects of potential sources of inclined waves and their impact on the design of the BWRX-300 SMR because the approach is consistent with the NRC guidance NUREG/CR–6896. The staff, in addition, takes assurance that the basis used for segregating the SH and SV waves is based on information in NUREG/CR–6896.

5.3.4 Approaches for Meeting DC/COL–ISG–017 Guidance

The intent of DC/COL–ISG–017, “Interim Staff Guidance on Ensuring Hazard Consistent Seismic Input for Site Response and Soil-Structure Interaction Analyses,” March 2010 (ADAMS Accession No. ML100570203), is to ensure that the deterministic SSI analysis of embedded RB structure uses ground motion inputs that are hazard consistent with the results of probabilistic SRA, described in Section 5.2, at the foundation bottom elevation and at ground surface. For the deeply embedded BWRX-300 RB structure, the same criterion is applied to other intermediate elevations throughout the height of the embedment to provide consistency between deterministic SSI analysis and probabilistic SRA through the entire depth of the embedment. The consistency between the free-field motion for the deterministic SSI analysis and probabilistic SRA is checked at the ground surface and at intermediate elevations along the embedment depth using the PBSRS and PBIRS developed, as described in Section 5.2.2 of the LTR. The elevations corresponding to significant V_S contrasts in the SSI soil profiles are included as intermediate elevations for the checks.

The LTR proposes any of the following three approaches for the consistency checks:

1. Perform the checks prescribed in Section 3.2.3, “SSI Analysis of Embedded Structures Including Embedment,” in Nuclear Energy Institute, (NEI) White Paper, “Consistent Site-Response/Soil-Structure Interaction Analysis and Evaluation,” June 2009 (ADAMS Accession Number ML091680715), (NEI, WP 2009) and discussed in LTR Section 5.3.4.1 to ensure that the horizontal and vertical FIRS applied to the model at the bottom of the RB foundation is adequate at the ground surface and throughout the embedment depth.

2. Envelop the results of three or more sets of SSI analyses, described in Section 5.3.4.2 of the LTR, performed with FIRS, PBSRS, and PBIRS defined input ground motions applied at the foundation bottom, ground surface, and intermediate elevations, respectively.

3. Perform the checks, as described in Section 5.3.4.3 of the LTR, only for the horizontal direction and using the vertical free-field input motion for the SSI analysis that is constrained along the embedment depth of the soil columns based on the V/H ratios used for the probabilistic SRA and following the methodology in EPRI Report 3002011804, “Advanced Nuclear Technology: Modeling Vertical Free-Field Motion for Soil-Structure Interaction of Embedded Structures,” 2018, described in Section 5.3.4.3.

As an alternative, the LTR proposes to conduct a probabilistic SSI analysis following the requirements of Section 5.5 of ASCE/SEI 4-16 that would satisfy the DC/COL–ISG–017.

The staff finds all the proposed approaches reasonable and suitable for demonstrating that a hazard consistent spectrum has been used in the design of the deeply embedded BWRX-300 RB structure and they are evaluated below.

5.3.4.1 NEI Checks of FIRS Defined Input Ground Motion

The staff has reviewed the information GEH has submitted in LTR Section 5.3.4.1. GEH would check the input motion to be applied at the bottom of the foundation of the structures following the procedure of NEI WP 2009. These checks would be conducted for both horizontal and vertical component of the ground motion by performing 1-D linear elastic SRA on the same set of strain-compatible compression wave velocity V_p and shear wave V_s velocity profiles used in the deterministic SSI analysis. For all V_s profiles, the free-field motions calculated in the horizontal direction at the ground surface and at selected intermediate elevations of the deeply embedded reactor are enveloped. Similarly, the motions in the vertical direction for all V_p profiles are enveloped. This enveloped motion at the ground surface would be compared with the horizontal and vertical PBSRS. The enveloped motion at all the intermediate elevations would be compared with the PBIRS.

The staff finds the approach described in this section of the LTR to be reasonable because it is consistent with the NEI WP 2009. However, the verification of the NEI checks will be a critical part of the staff review of a site-specific future license application of the BWRX-300 SMR.

5.3.4.2 FIRS and PBSRS Defined Input Ground Motions

In this approach, GEH proposes to envelop the results from multiple sets of SSI analyses using the BE, LB, and UB subgrade profiles with input motion compatible to:

1. The FIRS and applied at the bottom of the RB foundation in the SSI model.
2. The PBSRS and applied at the ground surface in the SSI model.
3. The PBIRS calculated at selected intermediate locations and applied at corresponding locations of the SSI model.

This proposed approach ensures that the free-field probabilistic site response analysis is enveloped by the design.

The staff finds this approach reasonable for demonstrating that a hazard consistent spectrum has been used for design of the BWRX-300 SMR as it is consistent with the guidance of DC/COL–ISG–017.

5.3.4.3 V/H Based Vertical SSI Input Motion

In this approach, the checks, as described in Section 3.2.3 of the NEI WP 2009, are conducted only in the horizontal direction. As discussed in EPRI 2018, the vertical motion applied at the foundation level amplifies as it reaches the ground surface and the V/H ratio exceeding the value determined at the site. This overestimation of the vertical design ground motion results in an overly conservative design of the structure and the equipment. GEH proposes to follow the method described in EPRI 2018. The site V/H ratio is used to develop the free-field ground motion for SSI analysis. GEH will check the accuracy of the vertical motion applied to the SSI model along the embedment depth at the free-field interaction nodes. The resulting V/H ratios are compared with the V/H ratios used to generate the vertical PBSRS and PBIRS.

The staff finds the proposed approach for demonstrating that a hazard consistent spectrum has been used to design the deeply embedded BWRX-300 RB structure to be reasonable and suitable because it uses the method suggested by EPRI 2018.

5.3.5 Effects of Variation of Structural Stiffness and Damping Properties

The modeling of appropriate stiffness and damping properties of the structural members in the SSI model is essential for the accuracy of the calculated seismic responses and seismic demands. The stiffness of concrete structural members, such as reinforced concrete or steel-plate composite (SC) members, depend on the degree of concrete cracking. Effects of concrete cracking on structural stiffness is considered by the following approaches.

Stiffnesses of the reinforced concrete members, calculated per ACI 349-13, are reduced based on the criteria provided in Table 3-1 of ASCE/SEI 43-05, “Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities,” 2005, to address the effects of cracking. The cracking status of a reinforced concrete member is evaluated based on the recommendations in Section 3.3.2 of ASCE/SEI 4-16, using the nominal concrete compressive strength (f_c') and the overall level of stress the structural member experiences under the earthquake design loads in combination with other applicable design loads. ASCE 43-19, “Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities,” 2019 is the latest update of the ASCE/SEI 43-05 standard. The effective stiffness of SC walls is determined based on Section N9.2.2 of AISC N690-18. The effective in-plane shear stiffness of SC walls is determined from the equations provided in Section N9.2.2(b) of AISC N690-18.

In accordance with SRP Section 3.7.2 and following the guidance and the requirements of Section 3.3.2 of ASCE 4-16, GEH states that the analyses will be performed on models that represent the uncracked stiffness properties of the concrete. Depending on the level of stress in the concrete due to the most critical seismic load combinations, effective stiffness values are assigned to the concrete members depending on their cracking status. The assignment of the stiffness properties to structural members follows the guidance in SRP Section 3.7.2.

GEH has proposed to use an optional approach, presented in Section C3.3.2 of ASCE/SEI 4-16, to design the BWRX-300 SMR. This approach uses the design-basis model with stiffness properties that yield conservative seismic responses and design for the site-specific conditions. This approach can also be used to address the effects of variations of structural stiffnesses. A third approach suggested in the LTR is to capture the structural stiffness variation using a sensitivity SSI analysis for the following bounding stiffness conditions:

a. A fully cracked condition when all concrete structural members are fully cracked and are assigned higher SSE damping properties; and

b. A fully uncracked condition when all concrete structural members are assigned full (uncracked concrete) stiffness and lower Operating Basis Earthquake (OBE) damping properties.

These sensitivity analyses are performed for the BE subgrade profile to evaluate possible amplifications of in-structure responses and load demands on the steel members from the load redistribution effects. These evaluations are based on comparisons of results from these two sensitivity analyses and the design-basis analysis performed for the BE profile using the BE dynamic properties for the RB structure. The comparisons are performed for in-structural responses and stress demands at key locations selected, as described in Section 5.3.1 of the LTR.

The damping ratio assigned to the structural members should be consistent with the cracked or uncracked state or as an alternate they can be assigned in accordance with Section C.1.2 of RG 1.61, “Damping Values for Seismic Design of Nuclear Power Plants,” Revision 1, March 2007 (ADAMS Accession No. ML070260029). The uncracked members in the models used for calculation of the ISRS and other in-structure response demands for seismic design and evaluation of seismic Category I (SC-I) equipment and components, are assigned lower OBE damping values.

The staff finds this approach to capture the variation of the stiffness of the structural model under the seismic event is reasonable because these methods are well established practices and captured in the industry consensus documents and RGs.

5.3.6 Dynamic Modeling of Subsystems, Components, and Equipment

In this section of the LTR, GEH proposes to include subsystems, components, and equipment (referring them collectively as equipment in subsequent discussion) in the SSI analysis model based on their mass ratios and first natural frequencies. The RPV will be modeled as a lumped-mass stick model capturing all significant seismic response. The equipment-structure interaction (ESI) effects would be explicitly considered in the analysis by using either of the three methods: (1) DM (explicitly modeling the equipment mass and stiffness), (2) Mass-Impedance ESI Method (mass of the equipment and dynamic stiffness represented as impedance), or (3) Generalized ESI Method (consideration of a secondary system with multiple degrees of freedom attached to the structure at multiple points). Modification of the ISRS due to ESI would be calculated.

The staff finds the proposed approaches reasonable because they are typically used in the industry. Whether a particular equipment should be included in the SSI analysis would be determined following the criteria described in Subsection II.3.B of SRP Section 3.7.2. The proposed three methods to analyze the ESI effects are also used in practice as outlined in EPRI Report 3002009429: “Advanced Nuclear Technology: High-Frequency Seismic Loading Evaluation for Standard Nuclear Power Plants,” 2017.

5.3.7 Modeling of Structure-Soil-Structure Interaction Effects

In LTR Section 5.3.7, GEH presents the approach to address the Structure-Soil-Structure interaction (SSSI) effects that result from the proximity of the RwB, CB, and TB on the SSI of the RB. The increased overburden from the buildings can have significant effect on the lateral loads applied to the RB below-grade walls and to some extent impact the RB SSI effect.

Simple models representing the BE dynamic properties of surrounding buildings and foundations will be included in the RB FE model used for the seismic SSI analysis. These simple models are sufficiently refined to capture all global modes of vibration of RwB, CB, and TB structures with significant (> 20%) modal mass participations in the three orthogonal directions.

The staff finds this approach to include the SSSI effects in the SSI analysis of the BWRX-300 RB structure reasonable because similar approaches have been used in prior licensing applications to include the effects of SSSI.

5.3.8 Excavation Support and Backfill Effects

The LTR states that the preferred method of construction of the BWRX-300 RB shaft is the open caisson method. The excavation for the shaft in softer soil strata is retained by a circular slurry shoring wall socketed into bedrock. The concrete structure for the RB is constructed bottom up within the caisson.

In LTR Section 5.3.8, GEH states that the BWRX-300 SMR design does not rely on the resistance provided by the slurry wall or other support systems used to secure the stability of excavation and the lean concrete used to fill the gap between the below-grade RB shaft exterior wall and the excavated soil and rock. These construction elements are temporary by design and are excluded from the models used for the static and dynamic SSI analysis because they are not expected to maintain their structural integrity through the entire operational life of the plant. The exclusion of the excavation supports and fill concrete results in conservative estimates of the static and dynamic lateral pressure demands on the RB below-grade walls.

The staff concludes that with the degradation of the excavation slurry wall the lateral soil pressures on the RB exterior wall computed based on K_0 would be smaller and, hence, using K_0 would provide a conservative estimate for the design demand.

The LTR also discusses the potential effects of the RB shaft construction and waterproofing on the friction at the interfaces between the exterior walls of the RB and the surrounding excavation support structure or the fill materials that may be used. GEH has proposed to conduct sensitivity analyses to address the uncertainties of the friction at the RB shaft interfaces by conducting analyses at two extreme frictional conditions: (1) fully bonded with no slippage, and (2) no frictional resistance. If the calculated ISRS and force demands at selected key locations (LTR Section 5.3.1) significantly (> 10%) differ from the results of design-basis SSI analyses, the results of these sensitivity analyses would be included in the RB seismic design-basis. The staff finds the proposed approach to be reasonable as it bounds the effects of friction from RB shaft construction and waterproofing and to assess their effects on the design-basis SSI analyses. In addition, a path forward is proposed if the effects are significant.

5.3.9 Soil Separation Effects

GEH has proposed in this section of the LTR to assess the effects of soil separation using the guidance in ASCE/SEI 4-16, Section 5.1.9(b) by comparing the difference between the seismic and the static lateral earth pressure on the wall of the RB shaft, calculated from the 1g static SSI analysis, in lieu of a nonlinear SSI analysis. The regions where the static lateral pressure $\rho_{LB}(z)$ is lower than the seismic lateral pressure calculated from the seismic SSI analysis indicate potential separation at the soil-structure interface.

The staff finds this approach to establish the non-contact surface over the height of the RB wall and the excavated face to be reasonable because the guidance in ASCE/SEI 4-16 Section 5.1.9(b) is a widely accepted consensus approach which consistently demonstrates acceptable results.

5.3.10 Groundwater Variation Effects

Variations in the groundwater level can change the dynamic properties of the subsurface soil/rock and affect the seismic response of the RB and the in-structure responses. GEH has proposed to address this issue by performing a sensitivity analysis using two extreme water level conditions: (1) a fully wet soil profile (simulating a flooded site) and (2) a dry soil profile (when ground water is assumed to be below the foundation level). Both analyses will be conducted using the BE dynamic soil properties. If the results vary greater than 10 percent at the key locations, the design-basis would be developed based on a fully saturated soil profile below the nominal groundwater table.

The staff finds this approach to addressing the effects of ground water table variation on the result of the seismic response of SSC's reasonable because the two extreme conditions considered in the analysis fully bound the effects of water table fluctuations on the seismic design of the RB.

5.3.11 Non-Linear Seismic SSI Analysis

If the site selected for constructing a BWRX-300 SMR is in a high seismic region and/or the subgrade materials exhibit highly nonlinear behavior, GEH proposes to use the nonlinear SSI analyses, following the guidance given in Appendix B of ASCE/SEI 4-16, to assess the importance of the following on the RB seismic response and design: (1) the secondary nonlinearity of the subgrade materials including nonlinearities introduced by the slip and opening of the rock discontinuities and (2) any nonlinearities introduced by separation and sliding of the soil/rock-structure interfaces. Although there is some evidence that plastic deformation of the subgrade materials reduces the structural response, especially at high frequencies, GEH proposes to analyze any potential amplification of the RB structural response from the secondary nonlinearity of the subgrade materials. The proposed analyses would particularly assess whether presence of fracture zones, rock joints, bedding planes, discontinuities, cavities, and other weak zones in the rock mass may significantly amplify the rock pressure loads and affect the block stability. These analyses will use nonlinear constitutive models with the BE properties of the subgrade materials, as recommended in Section B.4 of ASCE/SEI 4-16.

If the separation at the soil/rock-structure interface is found to be significant, as discussed in LTR Section 5.3.9, SSI analyses would be performed to explicitly assess the potential nonlinearities at these interfaces. Because the focus of these analyses is to assess the effects of the nonlinear behavior of the subgrade materials, the structural members would be assigned linear elastic properties with the BE stiffness and damping properties. GEH states that they will eliminate any unintended numerical damping introduced by the numerical integration in the SSI model. Additionally, the model boundaries should be placed at an adequate distance away to simulate the semi-infinite boundary conditions of the subgrade. The Domain Reduction Method may be used to analyze such scenarios to reduce computational resources. Following Section B.3 of ASCE/SEI 4-16, three components of the ground motion would be simultaneously applied to the SSI model. Results of the nonlinear SSI analyses would be compared with the linear elastic SSI analyses to assess the effects of these nonlinear phenomena at the subgrade in addition to the ISRS and member forces calculated. If the nonlinear effects are significantly more than 10 percent, GEH would adjust the seismic design of the RB structure to envelope the nonlinear effects.

The staff finds the intent to conduct nonlinear SSI analyses to capture the effects of any significant nonlinear response of the subgrade materials on the RB seismic response and design to be reasonable. The analyses would be conducted following the guidance given in Appendix B of ASCE/SEI 4-16, a nationally recognized standard. The proposal to compare the nonlinear SSI analysis results with those from the linear SSI analysis is also reasonable. As stated in SRP Section 3.7.2, the staff conducts a detailed review of all inelastic/nonlinear analyses. A L&C # 5 has been provided in Section 8.0 of this SE.

6.0 DESIGN APPROACH FOR II/I INTERACTION

GEH presents in this section of the LTR a graded approach with associated acceptance criteria for design and evaluations of the II/I interactions of the CB, TB, and RwB structures with the deeply embedded RB structure. CB, TB, and RwB structures are designed according to their seismic classification. Design of these structures would be evaluated for SSE and the design-basis tornadoes, hurricanes, and extreme wind loads to assess whether they meet II/I interaction guidance, as given in Subsection II.8 of SRP Section 3.7.2 and listed in Section 2.4 of this SE.

The evaluation should also demonstrate that no gross failure occurs in the CB, RwB, and TB structures. Additionally, the structural displacement from these events would be accommodated by the gap provided among these structures and the RB structure. Definitions of the design-basis tornadoes and hurricanes are from RG 1.76, “Design-Basis Tornado and Tornado Missiles for Nuclear Power Plants,” Revision 1, March 2007 (ADAMS Accession No. ML070360253) and RG 1.221, “Design-Basis Hurricane and Hurricane Missiles for Nuclear Power Plants,” Revision 0, October 2011 (ADAMS Accession No. ML110940300), respectively.

GEH proposes to conduct evaluations of the II/I interactions with limited inelastic deformations following guidance in Subsection II.8 of SRP Section 3.7.2. To satisfy Criterion C of Subsection II.8 of SRP Section 3.7.2, the gap would be considered adequate if it is larger than the absolute sum of displacements of each structure along the entire height considering construction tolerances. GEH states that gross failure of these structures would be prevented as they would be designed following the applicable design codes and standards.

The staff finds the description presented in this section of the proposed evaluations of the II/I interaction between the RB structure and the CB, TB, and RwB structures reasonable because the proposed evaluations are based on the guidance given in Subsection II.8 of SRP Section 3.7.2. In addition, construction tolerances would be included in determining the gaps among these structures, consistent with SRP Section 3.7.2, making the gap assessment robust.

6.1 Control Building, Turbine Building, and Radwaste Building Design Bases

In this section, GEH states that the CB and TB structures are considered non-seismic and the RwB structure is considered RW-IIa category, as specified in RG 1.143, “Design Guidance for Radioactive Waste Management Systems, Structures, and Components Installed in Light-Water-Cooled Nuclear Power Plants,” Revision 2, November 2001 (ADAMS Accession No. ML013100305), Section 5.1. These structures would be designed based on their seismic classification. The staff finds this classification of these structures reasonable as further evaluated below.

6.1.1 Non-Seismic Control Building and Turbine Building Structures and Foundations Design Bases

The staff has reviewed the discussion given in this section of the LTR regarding design and construction of the non-seismic CB and TB structures and their foundations. GEH proposes to design these non-seismic structures following Chapter 16, Structural Design, of International Code Council, “2018 IBC Code and Commentary,” 2018 and applicable provisions of

ASCE/SEI 7-16. Structural concrete will be designed in accordance with the requirements of Chapter 19 of IBC and ACI 318-14, “Building Code Requirements for Structural Concrete and Commentary,” 2014. The control room may be designed as a reinforced concrete structure within the steel-framed structure of the CB. The steel framed structure of the CB will be designed, fabricated, and constructed following Chapter 22 of IBC and AISC 360-16, “Specification for Structural Steel Buildings,” 2016. Both the CB and non-seismic portion of the TB would be designed as Risk Category IV structures. Design earthquake loads would be following Section 1613 of IBC and ASCE/SEI 7-16.

The staff finds that the use of building codes and national standards, such as ASCE/SEI 7-16, AISC 360-16, and ACI 318-14, to design, fabricate, and construct the non-seismic CB and TB structures to be reasonable. Use of Risk Category IV, defined in ASCE/SEI 7-16, for these structures is also appropriate because failure of these structures could pose a substantial hazard to the community.

6.1.2 Radwaste Category IIa Building Structure and Foundations Design Basis

The design guidance for radwaste structures provided in RG 1.143, is to, in part, address aspects of GDC 60 and 61 related to controlling the release of radioactive material and provides appropriate containment and confinement of radioactive material. RG 1.143 indicates that radwaste structures should be classified based on the potential radiological consequences of an unmitigated release to the public or unmitigated exposure to workers. The RW-IIa classification is the most robust design-specified in RG 1.143 for radwaste structures and RG 1.143 includes no upper limit on the unmitigated release or unmitigated exposure to workers from material in an RW-IIa structure. As a result, the staff finds that it is acceptable to classify the RwB structure as RW-IIa for the purposes of meeting the design guidance of RG 1.143.

LTR Section 1.3 stated that the portions of the TB structure and foundation that support and enclose the main steam piping and the Off-Gas System (OGS) for management of radiological gases are designed as RW-IIa following the provisions of RG 1.143. LTR Section 6.1.2, further stated that based on RG 1.143, Table 2, the loads for the design RW-IIa RwB and TB structures include one-half of the SSE seismic load. Because RG 1.143 only addresses Radioactive Waste Management Systems for which it provides guidance for the design, construction, installation, and testing the SSCs of radioactive waste management facilities in LWR nuclear power plants, GEH, in response to a staff RAI 01.05-1 dated August 19, 2021, indicated that it would move the OGS charcoal absorbers to the RwB, thereby eliminating the need for the associated portion of the TB to comply with RG 1.143. The response also stated that SSCs in the TB would not be relied on for accident mitigation and indicated that revisions would be made to Sections 1.3, 2.4, 6.1, and 6.4 of the LTR to reflect the relocation of the OGS absorbers. The staff reviewed Revision 1 of the LTR and confirmed the indicated revisions were made.

While the applicant discusses design aspects of the main steam system in the response to RAI 01.05-1, the LTR does not provide detailed design information for plant systems and does not request approval of the design of the main steam system and its associated SSCs. Therefore, the NRC staff will conduct the review of the system during future licensing activities when detailed design information for the system is submitted.

In addition, the staff notes that if following the guidance in RG 1.143, the radioactive waste management systems and components would also be given a radwaste classification based on the building classification and the quantities of radioactive material in the systems and components. However, the radwaste system design and the classification of radwaste systems are not addressed in the LTR. Therefore, the NRC staff will conduct the review of the systems during future licensing activities when detailed design information for the system is submitted.

Likewise, while the LTR discusses design aspects of the BWRX-300 structures, the LTR does not address any aspects of the radiation protection design (e.g., radiation shielding), other than the RW-IIa RwB classification. Therefore, the staff will conduct its reviews of these aspects during future licensing activities when detailed design information is submitted.

6.2 II/I Seismic Interaction Evaluations

GEH proposes to evaluate the CB, TB, and RwB structures for II/I interactions during an SSE event to ensure:

i. Integrity of the lateral load resisting members is not compromised.

ii. Stability of the foundations of these structures are not compromised in an SSE event.

iii. Gaps between the RB and these structures are adequate to prevent any physical interactions.

II/I seismic interactions would be evaluated using the calculated responses of these structures in an SSI analysis using linear material properties. Limited inelastic responses would be considered (Limit State C, as defined in ASCE/SEI 43-05. As an alternative, GEH has proposed to conduct the Fixed-Base analysis if any of three criteria in Section 5.1.1 of ASCE/SEI 4-16 is satisfied. The SSE demands, determined using the linear elastic seismic response analysis of the CB, TB, and RwB structures, would be reduced by an appropriate reduction factor given in Table 5-1 of ASCE/SEI 43-05. Sliding and overturning stability of the foundations would be evaluated using the results of seismic analyses. The gaps between the RB and other structures would be considered adequate if they are larger than the absolute sum of the SSE-driven displacement of each structure and evaluated along the entire height of the structure. In addition, construction tolerance would be included in the evaluation. The seismic displacements calculated from linear elastic seismic models would be converted to the inelastic displacements using a factor given in ASCE/SEI 41-17, “Seismic Evaluation and Retrofit of Existing Buildings,” 2017.

The staff has reviewed the discussion on the approaches proposed to evaluate the II/I interactions between the structures in a seismic event. The staff finds that the approaches to be reasonable because the approaches appropriately use guidance given in national standards in this assessment to satisfy Criterion C of Subsection II.8 of SRP Section 3.7.2, for assessment of seismic gap from an SSE event.

6.3 II/I Interaction Evaluations for Extreme Wind Loads

In this section of the LTR, GEH discusses evaluations of II/I interactions for extreme wind events. GEH states that interaction checks would be performed in accordance with the design codes and standards using the same analytical model without the SSI. RG 1.76 gives the appropriate wind speeds for tornado loads. RG 1.221 gives the wind speeds for hurricanes appropriate for a nuclear facility at a given location. Chapter 26 of ASCE/SEI 7-16 gives the design-basis straight-line wind speeds. The CB and TB are steel-braced structures designed in accordance with ANSI/AISC 360-16, “Specification for Structural Steel Buildings, American Institute of Steel Construction,” 2016. Limited inelastic response of these steel-braced frames would be permitted if the global stability is assured to check for interaction. ACI 349.3R (2010) requires structures to remain elastic in analyzed loadings. Therefore, the check for II/I interactions for RwB would be performed under controlling wind loads which maintain a linear elastic response. The RB structure is also designed against design-basis tornado missiles, given in RG 1.76, and hurricane missiles, given in RG 1.221. The RwB is also designed for tornado missile strikes.

The staff finds that the discussion given in checking for II/I interactions for a tornado, a hurricane, or an extreme wind event is reasonable because it uses national standards to check for any interactions among the structures in these events.

7.0 BWRX-300 SMR GENERIC DESIGN APPROACH

This section of the LTR describes the methodology to develop generic seismological and geotechnical site parameters for a wide range of conditions at candidate sites across North America. A detailed review of each section is provided below.

7.1 BWRX-300 SMR Structural Conceptual Design Approach

In this section of the LTR, GEH states that the BWRX-300 SMR is conceptually designed to use a lower amount of construction materials. GEH is also performing design calculations for sites with a range of geotechnical and seismological conditions representing at least 80 percent of all North American candidate sites. The majority of the safety-related components and equipment would be placed below-grade to mitigate potential effects of external hazards, such as adverse weather or aircraft crashes.

GEH also states that they have conducted seismic SSI response analysis using a FE model of the RB structure using eleven different generic soil profiles listed in LTR Table 7-1. GEH concludes that application of the generic conceptual design at these eleven different site conditions ensures economic viability of the BWRX-300 SMR. However, because the SSI results are not part of this LTR, the NRC staff did not evaluate the results.

7.2 BWRX-300 SMR Generic Design Response Spectra

The LTR Section 7.2 provides three generic design response spectra (GDRS) that are developed to be representative of a broad variety of regions across the United States. These three GDRS are all anchored at 0.3g for peak ground acceleration, which may not be representative of high-hazard sites. The LTR provides three response spectra for both horizontal and vertical components.

The NRC staff reviewed the GDRS and finds them to be consistent with the expected response spectra for regions across the United States, except for high-hazard sites. The GDRS are expected to meet the requirements of GDC 2 for low to moderate hazard sites, which comprise the majority of potential reactor sites within the United States.

7.3 Generic Profiles of Dynamic Subgrade Properties

The LTR Section 7.3 provides eight generic profiles for subsurface dynamic properties that are developed to be representative of a broad variety of candidate sites (LTR Figures 7-2 through 7-5). The profiles that are characterized here by the shear wave velocity range from low velocity sites (consistent with soil sites) to high velocity sites (representative of hard rock sites). The profiles were developed by grouping measurements from multiple sites with similar subsurface properties and geologies and averaging the results. The resulting profiles are broadly representative of a number of subsurface conditions and results from these generic profiles can inform seismic design in the generic BWRX-300 SMR structures.

The NRC staff has reviewed the generic subsurface profiles and finds them to be broadly consistent with conditions found across the U.S. However, the NRC staff notes that variation of these soil properties with depth are site-dependent. Additionally, it is not clear if these profiles specifically account for presence of a rock mass in the subsurface. Therefore, the staff cannot determine whether the profiles, as given in LTR Figures 7-2 through 7-5, would be appropriate for a site in the U.S. The staff notes that these variations of the dynamic properties in the subgrade of a site would need to be provided and evaluated by the staff during the review of any future site-specific licensing application.

7.4 BWRX-300 SMR Generic Design Soil Parameters

In this section, GEH discusses six soil engineering parameters to characterize different subgrade materials for the generic conceptual design of the BWRX-300 RB structure: (1) dry and total unit weights (W_s), (2) void ratio (e), (3) internal frictional angle $(\emptyset_s)$, (4) at-rest lateral pressure coefficient (K_0), (5) active lateral pressure coefficient (K_a), and (6) passive lateral pressure coefficient $\left(K_p\right)$. GEH has provided in LTR Table 7-2 the generic soil parameters given in the design manuals by the Iowa Department of Transportation. GEH has claimed that the properties of cohesionless soils given in Table 7-2 would adequately represent the generic candidate sites. This section also discusses how some of the properties are determined from other properties given in Table 7-2.

The NRC staff has reviewed the generic design soil properties and found them to be reasonable. However, it is not clear to the staff what the basis would be to claim that the generic design soil properties would represent at least 80 percent of candidate sites in North America. The staff notes that other parameters of the subsurface soil layers would be necessary to design the BWRX-300 RB structure at a specific site. Based on the preceding discussion, the staff cannot determine whether the generic design soil parameters would represent a site as they are site-specific parameters. The staff notes that the design soil parameters of the selected site would need to be provided and evaluated during the review of any future site-specific licensing application.

7.5 BWRX-300 SMR Generic Profiles of Static Subgrade Properties

In this section, GEH has presented eight generic profiles of variation of the unit weight, Young's modulus, and Poisson's ratio with depth, as shown in LTR Figures 7-6 through 7-8. These static properties are used to determine soil pressure demand. The approach to determine different parameter values has been discussed in this section.

The NRC staff has reviewed the generic profiles of these three subgrade material properties with depth and notes that profiles of dry unit weight, soil Young's modulus, and soil Poisson's ratio with depth, as given in LTR Figures 7-6 through 7-8, are dependent on the site. The staff cannot determine whether the variations in these profiles with depth would be appropriate without a site-specific basis, and specific details of the subsurface properties. As such, the staff notes that the subgrade properties of the selected site would need to be provided and evaluated during the review of any future site-specific licensing application.

7.6 BWRX-300 SMR Generic Design Base Shear Friction Coefficients

GEH has provided the generic values of the friction coefficient between the concrete basemats and different types of subgrade materials underlying the basemat, as given in LTR Table 7-2. GEH has not provided the source for these assumed values but described them as common engineering practice. The staff notes that the friction coefficient is a site-specific parameter to be measured from samples taken during site investigation.

The NRC staff has reviewed the friction coefficient of the reactor base and the medium lying immediately underneath it. The NRC staff notes that these assumed values pertain to the horizontal sliding surfaces at the bottom of the RB, RwB, TB, and CB foundations and are generic. GEH will measure the friction coefficient of the vertical wall between the RB shaft and the surrounding soil/rock media in a site-specific application as one of the interface (Figure 4-2) parameters, as discussed in LTR Section 3.1.2 and response to RAI 02.05.04-01 dated November 4, 2021. The staff notes that the friction coefficient is a site-specific parameter that would need to be measured, provided, and evaluated by the staff during the review of any future site-specific licensing application.

7.7 BWRX-300 SMR Generic Design Nominal Ground Water Level

GEH has used ground water pressure loads assuming two ground water elevations at the site in the generic BWRX-300 design:

I. At plant grade.
II. Below the RB foundation.

The same ground water level has been used in stability calculations to account for the buoyancy force. The staff notes that this load is due to ground water in the soil/rock matrix. At some sites, flow of ground water through a rock fracture at substantial pressure may also introduce additional load (response to NRC RAI Question 02.05.04-07). Whether flow of water through fracture(s) is significant is a site-specific condition. The staff notes that the presence of significant fracture flow at the selected site would need to be provided and evaluated by the staff during the review of any future licensing application.

8.0 LIMITATIONS AND CONDITIONS

If an applicant chooses to incorporate by reference the approaches, methodologies, and laboratory and field tests to be conducted at a site, or other discussions given in this LTR as part of a DC application, or if a license applicant uses it for requesting a construction permit and operating license under 10 CFR Part 50 or a combined license under 10 CFR Part 52, it must provide appropriate safety analyses to demonstrate compliance with the applicable regulatory requirements.

In addition, the applicant referencing the LTR for construction and design features as part of a license application for approval of a reactor design, construction, and/or operating license must address in their applications the following L&Cs or provide additional justification for any deviations.

8.1 L&C # 1 Interface Characteristics Testing

As discussed in SE Section 3.1.2, large size samples collected at a site should be tested in the laboratory to have an acceptable estimate of the measured discontinuity (e.g., rock-rock, rock-soil) and interface (e.g., rock/soil-structure) strength and deformation parameters for a nuclear power plant. The NRC staff will review the sizes of the samples and their testing at the laboratory to estimate the properties of the discontinuities and interfaces in a site-specific license application with a BWRX-300 SMR.

8.2 L&C # 2 Stable Excavation

As discussed in SE Section 5.1.2, a stable shaft excavation would have no unstable blocks in its surrounding that may slide into the excavation. A self-supported (even with some temporary reinforcement) excavation would be needed to place the RB and to estimate the earth pressure loads to be considered in the generic design of the RB structure. The NRC staff review of a site-specific application with the BWRX-300 SMR will focus on the method(s) used to identify the unstable rock blocks in the area surrounding the RB shaft and to assess the earth pressure imparted on the RB shaft for determining whether the subgrade is acceptable for siting the reactor. In addition, any temporary reinforcement or mitigation measures used to stabilize the surrounding materials would be reviewed by the staff.

8.3 L&C # 3 Isotropic and Homogeneous Rock Mass

As discussed in SE Section 5.2.1.2, the rock mass classification systems inherently assume isotropic and homogeneous rock mass. This assumption therefore implies that a jointed (or a fractured) rock mass contains a sufficient number of discontinuity sets so that its deformational behavior may be assumed to be isotropic and homogeneous. The NRC staff will review whether the discontinuity sets at the selected site would make the rock mass behavior isotropic and homogeneous in any future site-specific licensing application.

8.4 L&C # 4 Site Specific Application of the HCSCP

In Section 5.2.4 of the LTR, GEH proposed a new approach to develop the HCSCP. Although the approach is reasonable, it will be the first ever application to a nuclear reactor project. The staff notes that during the review of future licensing applications, the staff will audit the HCSCP approach.

8.5 L&C # 5 Nonlinear SSI Analysis

GEH proposed in Sections 5.3 and 5.3.11 of the LTR to conduct a nonlinear sensitivity SSI analysis, as necessary, to validate any nonlinear effects from high seismicity and/or subgrade materials on the RB seismic response and design. The NRC staff plans to review the characterization and modeling of the nonlinear behavior of the materials surrounding the reactor in any future licensing application utilizing a nonlinear SSI analysis approach.

9.0 CONCLUSION

Based on the above discussion, the NRC staff concludes that the proposed construction and design approaches for the BWRX-300 SMR, as described in this LTR, are acceptable with some limitations and conditions. In particular, the LTR describes approaches to address the design analysis and construction of a BWRX-300 nuclear plant with a proposed below-grade RB shaft. Also, as discussed in this SE, GEH has indicated that the detailed design of the BWRX-300 SMR has not been complete at this time. As such, until the detailed design is completed, or the identified site-specific aspects are identified, five L&Cs for the use of this report are identified and summarized in Section 8 of this SE.

Additionally, as stated above, upon implementation of this LTR into a site-specific application of the BWRX-300 design, the staff will evaluate each topical area designated above to ensure that each topic appropriately interfaces with the proposed license application to ensure consistency. The staff will also make its regulatory determinations regarding the topics discussed above, as applicable, during its review of any future license application.