SSI ANALYSIS METHODOLOGY AND RESULTS OF NI BUILDINGS OF THE APR1400 STANDARD PLANT

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ABSTRACT

This technical report provides the soil-structure interaction analysis methodology and results for the APR1400 Nuclear Island structures. The Nuclear Island structures are the Reactor Containment Building and Auxiliary Building founded on a monolithic common basemat.

The nine generic site profile cases plus a fixed-base case are considered in the seismic analysis. The free-field site response analysis is performed for development of the free-field-strain-compatible dynamic soil and rock properties used in the soil-structure interaction modeling of the Nuclear Island structures.

The soil-structure interaction analysis generates maximum seismic response parameters, which include the maximum seismic response absolute accelerations, relative displacements, building structural forces and moments under the design-basis seismic ground motion input for use in the structural design of Nuclear Island structures. The analysis also generates the in-structure response spectra for the seismic response motions for use in seismic analysis or qualification of the equipments, subsystems, and components housed in the Nuclear Island structures. For soil-structure interaction analysis of Nuclear Island structures, both uncracked and cracked concrete stiffness conditions are considered for each case of generic site profiles and the fixed-base case. The operating basis earthquake damping values in NRC Regulatory Guide 1.61, Revision 1, are used for the uncracked concrete condition, and the safe shutdown earthquake damping values are used for the cracked concrete condition.

The soil-structure interaction analysis is performed using the SASSI analysis methodology and the associated SASSI computer program. The Direct Method (Flexible Volume Method) of SASSI substructuring is used in the soil-structure interaction analysis. The maximum seismic response parameters and in-structure response spectra generated from the fixed-base seismic response analysis are enveloped with the corresponding results of the seismic soil-structure interaction analysis performed for the nine generic site profile cases to produce the final enveloped maximum seismic response parameters and in-structure response spectra for standard design.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

List of Acronyms

3-D	Three-dimensional
AB	Auxiliary Building
AFW	Auxiliary Feed Water
CMS1+	Control Motion Spectra 1+
CPB	Compound Building
CS	Containment Structure
CSDRS	Certified Seismic Design Response Spectra
DOF	Degrees of Freedom
DRS	Design Response Spectra
EDGB	Emergency Diesel Generator Building
E-W	East-West
FEM	Finite Element Model
FHA	Fuel Handling Area
ICI	In-Core Instrumentation
IRWST	In-Containment Refueling Water Storage Tank
IS	Internal Structure
ISRS	In-Structure Response Spectra
NI	Nuclear Island
N-S	North-South
OBE	Operating Basis Earthquake
PGA	Peak Ground Acceleration
PSD	Power Spectral Density
PSW	Primary Shield Wall
PZR	Pressurizer
RCB	Reactor Containment Building
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RV	Reactor Vessel
SFG	Structural Fill Granular
SG	Steam Generator
SRP	Standard Review Plan
SRSS	Square Root of Sum of Squares
SSE	Safe Shutdown Earthquake
SSI	Soil-Structure Interaction
SSW	Secondary Shield Wall
TGB	Turbine Generator Building
ZPA	Zero-period Acceleration

1.0 INTRODUCTION

This technical report presents the soil-structure interaction (SSI) analysis methodologies and results for the Nuclear Island (NI) structures of the APR1400 standard plant. The seismic ground motion input, site conditions, dynamic models, and analysis methodology and procedures used in carrying out the seismic analysis are described in this report. The key analysis results are also presented.

The NI structures are the Reactor Containment Building (RCB) and Auxiliary Building (AB), which are founded on a monolithic common basemat. The RCB is structurally separated from the AB with a minimum seismic gap of 2 in above the common basemat. The RCB is a Seismic Category I structure that consists of a pre-stressed concrete cylindrical shell and hemispherical dome and a reinforced concrete internal structure that are supported by a reinforced concrete mat foundation.

The AB wraps around the RCB leaving a space as a seismic gap above the common basemat. The AB is a Seismic Category I structure that consists of reinforced concrete shear walls and floor slabs which are lateral load-resisting systems and frames that support the vertical loads.

The NI seismic analysis described in this technical report provides the maximum seismic response (demand) parameters, which include maximum seismic response absolute accelerations, relative displacements, building structural forces and moments under the design-basis seismic ground motion input for use in the structural design of NI structures. The analysis is also used to generate the in-structure response spectra (ISRS) for the seismic response motions for use in seismic analysis or qualification of the equipments, subsystems, and components housed in the NI structures.

The seismic analysis of NI structures described in this report includes seismic soil-structure interaction (SSI) analyses of the RCB and AB supported on nine (9) generic site-profile cases plus a fixed-base case analysis.

Since the RCB and AB share a common basemat, the seismic SSI analysis is performed for the combined NI structures (i.e., the combined RCB and AB supported on a common basemat foundation). The SSI analysis is performed using the SASSI analysis methodology and the associated SASSI computer program (Reference 9). The Direct Method or the Flexible Volume Method of SASSI substructuring is used in the SSI analysis. The maximum seismic response parameters and ISRS generated from the fixed-base seismic response analysis case are enveloped with the corresponding results of the seismic SSI analysis performed for the nine generic site profile cases to produce the final enveloped maximum seismic response parameters and ISRS for the standard design.

This technical report consists of seven (7) sections. Section 1 provides an introductory note and background information. Section 2 describes design ground motion developed for seismic analysis of the APR1400. Section 3 presents a description of the NI structures. Section 4 describes the generic site profiles and site response analysis for the SSI analysis. Section 5 describes the SSI analysis for the NI structures. Section 6 provides the SSI analysis results of the NI structures. References cited in this technical report are listed in Section 7.

Numerical data and results are presented in Appendices A through G.

2.0 DESIGN GROUND MOTION

The basic seismic design input parameters used in the seismic analysis of the NI structures consist of (a) the design ground motion for the Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE) conditions and (b) design time histories.

For the APR1400, the design ground motion for the SSE considered in the seismic design consists of two sets of ground motion parameters: (a) horizontal and vertical design (ground motion) response spectra anchored to a peak ground acceleration (PGA) of 0.3g, where g is the acceleration of gravity, and (b) horizontal and vertical design time histories associated with the design response spectra (DRS).

For the APR1400 design, the design ground motion for an OBE is set to one-third (1/3) of the SSE. Thus, in accordance with the NRC Standard Review Plan (SRP) Section 3.7.1, Revision 3, guidelines (Reference 10), a seismic analysis or design for an OBE is not required. Only the design ground motion for the SSE is considered for the seismic analysis of the NI structures.

2.1 Design Response Spectra

The DRS for the SSE used for the APR1400 design, which are designated as “Certified Seismic Design Response Spectra (CSDRS),” are DRS enhanced from the “CMS1+” DRS (Reference 8). The CMS1+ DRS are response spectra used for the APR1400 reference plant design, namely, the Shin-Kori Unit 3 and 4 plants in Korea. The “CMS1+” DRS is enhanced using design response spectral amplitude in a high frequency range from 25 to 40 Hz.

Recent seismic analyses performed for nuclear power plant structures constructed on Central and Eastern United States (CEUS) hard rock sites have been conducted with a high-frequency cut-off at 50 Hz. This practice is based on the guidelines in SRP Section 3.7.1 (Reference 10) in which the minimum power spectral density (PSD) function for the horizontal spectrum for CEUS rock sites has a high-frequency cut-off at 50 Hz. It is also based on Interim Staff Guidance 01 (ISG-01) (Reference 11). ISG-01, Section 3, Article 3.1.1, states that the range of high frequency motion to be transmitted covers a model refinement frequency of at least 50 Hz.

To comply with the 50 Hz cut-off-frequency guidelines, the frequency at which the APR1400 CSDRS converge to the PGA value (rigid cut-off frequency) is extended from 33 Hz for the NRC RG 1.60 DRS to 50 Hz. The spectral values for frequencies between 25 to 50 Hz are obtained by linear interpolation on a log-log scale from 1.3 times the NRC RG 1.60 spectral values at 25 Hz and the PGA value of 0.3g at 50 Hz.

Figures 2-1 and 2-2 are comparisons of the 5%-damped, horizontal and vertical APR1400 CSDRS, CMS1+ DRS, and NRC RG 1.60 DRS, respectively. The enhancement of spectral values in the high frequency range for the APR1400 CSDRS and CMS1+ DRS as compared to the NRC RG 1.60 DRS can be identified from the comparisons in the figures.

Based on the guidelines of SRP Section 3.7.1, Revision 3, the APR1400 CSDRS for different damping ratios are constructed using the response spectral amplification factors in Tables 1 and 2 of NRC RG 1.60 (Reference 12). The horizontal and vertical APR1400 CSDRS for SSE that were constructed for spectral damping ratios of 2, 3, 4, 5, 7, and 10% used for design of the APR1400 are shown in Figures 2-3 and 2-4

respectively. The numerical values of spectral amplifications at the control frequencies are provided in Tables 2-1 and 2-2.

The APR1400 CSDRS for the SSE defined in the previous paragraph are response spectra for the free-field ground surface or hypothetical outcrop motion on top of the uppermost competent soil layer of the generic site profiles considered for the design.

2.2 Design Time Histories

The design time histories used for the seismic analysis of the NI structures are a single set of three-component (two horizontal designated as "H1" and "H2," and one vertical designated "VT") CSDRS-compatible acceleration time histories generated from a set of recorded actual earthquake accelerograms as the initial seed motion. The CSDRS-compatible acceleration time histories generated for the design of the APR1400 satisfy the response-spectrum and PSD enveloping guidelines and the acceptance criteria of SRP, Section 3.7.1, Revision 3, Option 1 – Single Set of Time Histories, Approach 1. Details of the development of the APR1400 CSDRS-compatible design time histories are described in the technical report "Seismic Design Bases for the APR1400 Standard Plant Design" (Reference 6).

The design acceleration time histories that are compatible with the APR1400 CSDRS for damping ratios of 2, 3, 4, 5, 7, and 10% are shown in Figures 2-5, 2-6, and 2-7, for H1, H2 and VT components, respectively. Component H1 is applied in the E-W (global X) direction, component H2 is applied in the N-S (global Y) direction and component VT is applied in the vertical (global Z) direction.

The cross-correlation coefficients of the generated time histories are verified. The cross-correlation coefficients for the generated three-component time histories are as follows:

$\rho_{XY} = 0.032$, $\rho_{XZ} = 0.079$ and $\rho_{YZ} = 0.029$

Where X, Y, and Z are the three global directions.

Because the three cross-correlation coefficients are less than 0.16 as specified in SRP 3.7.1 Section 3.7.1, it is concluded that these components are statistically independent.

3.0 DESCRIPTION OF NI STRUCTURES

This section contains a description of the NI structures. The NI structures are classified as safety-related Seismic Category I structures. The RCB and AB are separate from each other, are above the basemat, and have a minimum 2 in seismic gap between them. In the plant layout, the AB wraps around the RCB. The finished grade of the plant is at El. 98’-8”. The top of the NI common basemat is at El. 55’-0”. Thus, the exterior walls of the AB are embedded to a depth of about 44 ft below the finished grade of the plant. The thickness of the NI reinforced concrete basemat is nominally 10 ft. The methodology and results used to develop the finite element models for the APR1400 NI structures are presented in Technical Report APR1400-E-S-NR-13002-P, “Finite Element Seismic Models for SSI Analyses of the NI Buildings of the APR1400 Standard Plant” (Reference 7).

3.1 Description of RCB Structures

The RCB of the APR1400 is a safety-related Seismic Category I structure and comprises the following three concrete sub-structures:

- Containment Structure (CS)
- Primary Shield Wall (PSW)
- Secondary Shield Wall (SSW)

The CS is also referred to as a pre-stressed concrete containment vessel. The PSW and SSW are combined to form the reinforced concrete Internal Structure (IS) and are the supporting structures for the Reactor Coolant System (RCS).

The CS and IS are separated by a 2 in gap and are connected only at their basemat at El. 78’-0”. There is no interaction between the two structures except through the common basemat. Figures A-1 through A-7 in Appendix A show the section and plan views of the RCB.

3.1.1 Containment Structure

The CS is a cylindrical post-tensioned shell with 4.5 ft thick walls. The dome is hemispherical with 4 ft thick walls. The intersection of the cylindrical and hemispherical shapes is called the spring-line and is at El. 254’-6”.

The CS has four openings, as follows:

- Each opening has a diameter of 11.16 ft.

Two of the openings are the north side, and two are on the east side.

- The personnel emergency exit airlock opening (one on the north side and one on the east side) is at center El. 103’-9” and azimuth 280°.
- The personnel access airlock opening (one on the north side and one on the east side) is at center El. 159’-9” and azimuth 234°.

The CS also has one equipment hatch opening.

- The opening is on the east side, has a 26 ft circular opening, and is at center elevation of 167'-6" and at azimuth 280°.

The CS has three 14 ft wide buttresses with thicknesses varying from 7.0 ft to 7.5 ft. The buttresses are 120 degrees apart. The first buttress starts at azimuth 30° from the north. See Figure 3-1.

The CS cylindrical shell is supported on the RCB concrete foundation base at El. 78'-0". The interior of shell structure is lined with 0.25 in thick steel liner plate, which acts compositely with the CS.

A polar crane is supported by the CS shell ring beam at El. 241'-0". Polar crane bridge girders and a trolley system are supported by an inner steel ring beam with a 71.62 ft radius that is offset by approximately 5.6 ft from the CS shell centerline using steel corbels (brackets).

3.1.2 Primary Shield Wall

The IS consists of two parts: the Primary Shield Wall (PSW) and Secondary Shield Wall (SSW). The IS is supported by the concrete basemat extending from El. 45'-0" to El. 78'-0". Figure 3-2 is an isometric view of the IS.

The PSW is a concrete rectangular block with an area of 61'-8" x 37'-6" and extends from El. 69'-0" to El. 130'-0". The PSW supports two E-W walls with variable thicknesses, which extend from the top of the rectangular block at El. 130'-0" up to a top elevation of 191'-0". The PSW has a 24 ft diameter opening that houses the Reactor Vessel on the east side. The west side of the PSW houses the In-Core Instrumentation (ICI) Cavity.

The top of the concrete for the ICI Cavity is at El. 106'-6" on the west side. The Refueling Pool is at El. 114'-0" on the east side between the PSW and SSW. The concrete block has six openings, each with a 6 ft diameter, which allow the hot and cold legs to penetrate the rectangular block that connects to the reactor vessel. Inside the concrete pedestal support there is a Reactor Cavity (pit) below the Reactor Vessel that extends from El. 69'-0" to El. 78'-0".

3.1.3 Secondary Shield Wall

The SSW has a cylindrical perimeter wall with a 51 ft radius (at the centerline) that protects the PSW. The SSW is 4 ft thick from top to bottom. The SSW acts as the primary supporting structure for the connecting slabs that span the PSW and SSW and the SSW and CS.

The connecting slabs are located at El. 114'-0", 136'-6" and 156'-0" (operating deck). The space between the SSW and PSW between at El. 78'-0" and El. 100'-0" is filled with a ring of concrete. The ring of concrete has a radius of 51 ft and is penetrated by the rectangular block of the PSW.

The major components of the SSW are:

- In-Containment Refueling Water Storage Tank (IRWST)
- Pressurizer (PZR) shaft

The IRWST is an annular cylindrical tank that is 26 ft wide, 22 ft high, and has 3 ft thick exterior walls. The tank is separated from the CS by a 2 in gap and is supported on top of the basemat. The tank roof slab is supporting the IS slabs above, which creates a vertical load path to the basemat.

The PZR structure is located at the North-West corner and is made of four (4) 2.75 ft thick concrete walls forming a square that extends to El. 200'-0". The PZR walls are 21 ft long and are directly supported by both the Secondary and Primary Shield Walls.

3.1.4 Reactor Coolant System

The major RCS components are listed below and shown in Figure 3-3:

- Reactor Vessel (RV) , which is supported by four columns and the PSW
- Two Steam Generators (SG), which are supported horizontally by the PSW and SSW and vertically at the base by concrete pedestals at El. 112'-10"
- Four (4) Reactor Coolant Pumps (RCP), which are supported laterally on beams spanning the PSW and SSW (at two elevations) and vertically (gravity) on a concrete pedestal at El. 103'-0"
- The Pressurizer (PZR), which is supported laterally by its own encasement walls (shaft) and vertically by a concrete slab at its base

3.2 Description of AB Structure

The Auxiliary Building (AB) is a safety-related Seismic Category I structure with an embedment depth of approximately 54 ft. It encloses the RCB in the center without a structural connection except at the common basemat.

The AB is a rectangular, reinforced concrete structure. The building includes the electrical and control areas, main steam valve house, chemical and volume control system areas, emergency diesel generator area, fuel handling area, spent fuel pool, cask loading pit, refueling canal, and auxiliary feed water (AFW) tanks.

The AB is bordered on the west by the Turbine Generator Building (TGB), on part of the south side by the Compound Building (CPB), and on part of the east side by the Emergency Diesel Generator Building (EDGB). The gaps between the AB and TGB, between the AB and CPB, and between the AB and EDGB are 3 ft. Gaps below the finished grade of the plant are backfilled with compacted structural fill granular (SFG).

The AB structure comprises reinforced concrete shear walls in the E-W and N-S directions for lateral load resistance and a composite of reinforced concrete walls and slabs with main columns and girders for vertical load resistance.

Figure 3-4 is an isometric view of the AB structure.

4.0 GENERIC SITE PROFILES AND SITE RESPONSE ANALYSIS

The APR1400 standard plant design considers that the plant is supported by various generic site profiles. Nine (9) generic site profiles and one fixed-base support condition are considered. The nine generic site profiles are horizontally layered sites with site shear wave velocities that vary from soft to medium to firm soil sites and from soft to medium to hard rock sites. A free-field site response analysis is performed for each generic site profile to develop the free-field-site-response-strain-compatible soil/rock dynamic properties to be used as input for the seismic SSI analysis of the NI structures.

The nine generic site profiles and the free-field site response analyses are described in the following subsections.

4.1 Generic Site Profiles

The nine (9) generic site profiles considered for the APR1400 standard plant design are divided among six (6) site-layering categories (Site-Layering Categories A through F) with site-layer thicknesses and depths from the ground surface as follows:

Site-Layering Category	Layer Thickness (ft)	Layer Depth Range (ft)
A	55	0 ~ 55
B	45	55 ~ 100
C	100	100 ~ 200
D	300	200 ~ 500
E	500	500 ~ 1000
F	Infinite	Halfspace > 1000

In addition to the six (6) site-layering categories, five (5) average-shear-wave-velocity categories (P1 through P5) are considered. The categories and associated average shear-wave-velocity values are as follows:

Average-Shear-Wave-Velocity Category	Average Shear Wave Velocity (ft/sec)
P1	1,200
P2	2,000
P3	4,000
P4	6,000
P5	9,200

The site soil/rock material unit weight (weight density), Poisson's ratio, and types of shear-strain-dependent modulus-degradation and damping-value-variation curves for the soil/rock material (sand, soft rock, and rock) considered for categories P1 through P5 are provided in Table 4-1.

The nine (9) generic site profiles considered for the APR1400 standard plant design are designated as S1 through S9 and are developed with combinations of the site-layering categories A through F and the average-shear-wave-velocity categories P1 through P5, as shown in Table 4-2. Figure 4-1 shows the low-strain shear wave velocity profiles versus depth for the nine generic site profiles considered.

The compression wave velocity profiles versus depths for the nine generic site profiles are derived from the low-strain shear wave velocity profiles and their corresponding Poisson's ratios shown in Table 4-1 using the following formula:

$$V_p = \sqrt{\frac{2(1-\nu)}{1-2\nu}}\ V_s \tag{4-1}$$

Where V_s = Shear wave velocity,

V_p = Compression wave velocity

ν = Poisson's ratio.

The shear-strain-dependent, soil/rock-modulus-degradation and damping-value variation curves for the soil/rock materials considered for the nine generic site profiles are shown in Figure 4-2 (sand), Figure 4-3 (soft rock), and Figure 4-4 (rock). The curves for sand, as shown in Figure 4-2, adopt the sand curves in an EPRI report (Reference 16). The curves for soft rock, as shown in Figure 4-3, adopt the curves for soft rock in Silva's report (Reference 17). The curves for rock considered, as shown in Figure 4-4, adopt the curves for rock used in the SHAKE computer program (Reference 18).

4.2 Backfill Material

For the APR1400 standard plant, backfill material used for backfill adjacent to the Seismic Category I structures is structural fill granular (SFG). In accordance with the APR1400 Design Criteria Manual (Reference 1), the reference low-strain dynamic shear modulus (G_{max}) of SFG in units of kg/cm^2 (1 kg/cm^2 = 2.0439 kip/ft^2 or ksf) is derived as follows:

$$G_{max} = 2{,}000 \times \sqrt{\sigma_m} \tag{4-2}$$

Where σ_m = Mean confining pressure in kg/cm^2.

The total and saturated weight densities (unit weights) of SFG are 137 and 140 pcf, respectively, and the dynamic Poison's ratio is 0.33.

For the standard design, the reference shear-strain-dependent modulus-degradation and damping-value-variation curves for the SFG considered are shown in Figure 4-5.

4.3 Groundwater Table Elevation

For the APR1400 standard plant design, the design groundwater table elevation is 2 ft below the ground surface at El. 96'-8". The extreme groundwater table elevation considered in the design is at a ground surface of El. 98'-8". If the compression wave velocity (V_p) of subgrade soil computed from the low-strain shear wave velocity and Poisson's ratio using Eq. (4-1) has a value less than the V_p of water (4,800 ft/sec), the V_p value of the soil is considered to be not less than 4,800 ft/sec.

4.4 Free-field Site Response Analysis

Horizontal free-field site response analyses are conducted for the nine generic site profiles S1 through S9 and subjected to the free-field seismic ground motion input at the ground surface at El. 98'-8". The free-field seismic ground motion input are the CSDRS-compatible acceleration time histories H1 and H2 applied in the plant E-W and N-S directions, respectively.

For each generic site profile, a horizontal free-field site response analysis is performed for H1 (E-W) and H2 (N-S) time history inputs using the SHAKE computer program (Reference 18). The shear-strain-compatible shear wave velocity profiles obtained from the analyses using H1 and H2 seismic inputs are then averaged to produce the averaged shear-strain-compatible shear-wave-velocity profile for each generic site profile. The averaged shear-strain-compatible shear-wave-velocity profiles obtained for S1 through S9 are the free-field site profiles used to develop the seismic SSI analysis models.

For the free-field site response analysis for each generic site profile, a low-strain soil column model is developed for use in the SHAKE analysis. The SHAKE soil column models are developed to pass vertically propagating plane seismic shear waves up to a cut-off frequency of at least 50 Hz. The SHAKE soil column models developed for all nine generic site profiles are tabulated in Appendix B, Tables B-1 through B-9. The averaged shear-strain-compatible shear-wave-velocity profiles obtained from the SHAKE soil column analyses and the associated compression-wave-velocity profiles for all nine generic site profiles are tabulated in Appendix B, Tables B-10 through B-18.

Using the averaged shear-strain-compatible shear wave velocity profiles as tabulated in Appendix B, Tables B-10 through B-18, the free-field site response amplification (transfer) function computed for the horizontal ground surface motion relative to the horizontal motion at depth at the top of the half space for profiles S1 through S9 is plotted, as shown in Figure 4-6.

The fundamental horizontal site frequencies for profiles S1 through S9, as shown in Figure 4-6, are tabulated in Table 4-3 and plotted in Figure 4-7. As indicated in Table 4-3 and Figure 4-7, the fundamental horizontal site frequencies for profiles S1 through S9 range from 1.27 to 12 Hz. The site frequencies form an approximate log linear site-frequency-versus-site-profile-case straight line. Hence, profiles S1 through S9 represent a wide range of site frequencies from soft soil sites to hard rock sites.

The dynamic properties for the free-field generic site profiles S1 through S9, given in Appendix B, Tables B-10 through B-18, are the properties that are used to develop the free-field soil/rock models for the SSI analyses of the NI structures.

4.5 Strain-Compatible Dynamic Properties of Backfill

For the SFG backfill material that is used next to the exterior walls of Seismic Category I structures from the ground surface to an embedment depth of 55 ft, the low-strain shear-wave-velocity profile are obtained from the low-strain shear modulus, G_{max}, values computed from Eq. (4-2). The compression-wave-velocity profile of SFG associated with the low-strain shear-wave-velocity profile is derived from the low-strain shear-wave-velocity profile and Poisson's ratio of SFG, which is equal to 0.33. Because the SFG backfill is below the maximum design groundwater table elevation at the ground surface, the derived compression wave velocity values that are less than the compression wave velocity of water (4,800 ft/sec) are replaced by a value of 4,800 ft/sec.

The shear-strain-compatible shear-wave-velocity profiles for the SFG backfill are obtained from the computed low-strain shear-wave-velocity profile and the shear-modulus-degradation and damping-variation curves shown in Figure 4-5, using the averaged horizontal shear strains computed from the free-field site response analyses for the generic site profiles S1 through S9. The profiles computed for the generic site profiles S1 through S9 are tabulated in Appendix B, Tables B-19 through B-27.

The dynamic properties of SFG computed for the generic site profiles S1 through S9, which are given in Appendix B, Tables B-19 through B-27, are the properties that are used to develop the SFG backfill models for the SSI analyses of the NI structures.

5.0 SOIL-STRUCTURE INTERACTION ANALYSIS

For the design of the APR1400 RCB and AB, seismic soil-structure interaction (SSI) analyses are performed for the NI structures that are supported on a common basemat. The SSI analyses are performed for all nine (9) generic site profiles S1 through S9 and one analysis case with a rigid uniform halfspace supporting medium that simulates the fixed-base analysis case (S10).

Both uncracked and cracked concrete stiffness cases are considered in the SSI analyses. For the uncracked concrete stiffness cases, the SSI cases that are analyzed are designated as S1U through S10U. For the cracked concrete stiffness cases, the SSI analysis cases are designated as S1C through S10C.

5.1 SSI Analysis Methodology and Computer Program

For the APR1400 standard plant design, seismic SSI analyses are performed using the 3-D finite-element SASSI analysis methodology (Reference 9) and the associated SASSI computer program (Reference 15). Because the NI structures of the APR1400 standard plant are embedded in site soil/rock media to a depth of 55 ft below the finished grade of the plant, the seismic SSI analyses performed using SASSI explicitly consider the 55 ft embedment effect on the seismic response. Following the SASSI analysis methodology, the foundation embedment is considered in the SASSI analysis using the Direct (or Flexible Volume) Method of substructuring.

Since the Direct Method is adopted for the SASSI analyses of 55 ft embedded NI structures, which are modeled using finite element models (FEMs), the resulting SASSI analysis models developed for the SASSI analyses contain a large number of dynamic degrees of freedom (DOF) along with a large number of SSI nodal DOF below grade. As a result, in order to generate seismic SSI responses for all 20 analysis cases described above within a reasonable computer solution time, the presently available large capacity Fast Solver Version of the ACS-SASSI computer program (Reference 15) is adopted to perform the SASSI computations.

5.2 Soil-Structure Interaction Models

The SSI analysis models developed for the APR1400 NI structures consist of three substructure models: a free-field site model, an excavated soil volume model, and a structure model including the backfill model.

<u>Free-Field Site Models</u>

The SASSI free-field site models are the same as the shear-strain-compatible free-field site models obtained from the free-field site response analyses described in Section 4.0. The dynamic soil/rock properties used for the SASSI site models are the average shear-strain-compatible soil/rock dynamic properties shown in Appendix B, Tables B-10 through B-18, for the generic site profiles S1 through S9. The layering configuration of the SASSI free-field site models is maintained for all nine site profiles. The maximum wave passage frequencies resulting from the layering configuration of the free-field site model for site profiles S1 through S9 are listed in Table 5-1. As indicated in Table 5-1, the maximum wave passage frequencies of the model vary from approximately 18 to 119 Hz.

Excavated Soil Volume Models

The NI structure site is excavated to El. 42’-0”, which is 3 ft below the bottom of the NI structure basemat. Three-dimensional (3-D) solid elements are used to model the excavated soil volume. The FEM developed for the excavated soil volume of the NI structure foundation, including the over excavation for the backfill, is shown in Figure 5-1. This model configuration is maintained for the nine generic site profile S1 through S9. The model contains a total of 9,254 nodes. Each node has three (3) dynamic DOF. The model consists of five (5) horizontal soil/rock layers from the ground surface at El. 98’-8”. The actual ground surface elevation in the model is taken at El. 98’-6” down to the bottom of the basemat at El. 45’-0” plus a sixth (6th) soil/rock layer of 3 ft thickness from El. 45’-0” down to El. 42’-0”. The extra excavated soil/rock layer accommodates the lean concrete backfill beneath the basemat
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Structure Model of NI Structures and Backfill

The structure model for the NI structures is the SASSI FEM obtained from conversion of the ANSYS coarse-mesh FEM developed for the RCB and AB as described in Technical Report APR1400-E-S-NR-13002-P, “Finite Element Seismic Models for SSI Analyses of the NI Buildings of the APR1400 Standard Plant” (Reference 7). The configuration of the combined SASSI FEM for the RCB and AB supported on the common basemat is shown in Figure 5-2.

The gap between the sidewalls of the site excavation pit and the exterior walls of the AB and the 3 ft wide gap between the AB and the adjacent CPB on the west side and the TGB on the south side are backfilled with compacted SFG. Under the NI common basemat, a layer of lean concrete approximately 3 ft thick is backfilled between the bottom of the basemat and the base of the soil/rock excavation pit. The material properties of the lean concrete backfill are presented in Table 5-2.

The SFG and lean concrete backfill in the SASSI structure model are modeled using 3-D solid elements. The configuration of the FEM developed for the SFG and lean concrete backfill is shown in Figure 5-3.

Complete SASSI Model for the NI Structures

The complete SASSI model is plotted in Figure 5-4. The model is composed of the free-field site model without the excavated soil volume model, as shown in Figure 5-1, and the addition of the combined structure model of RCB and AB, as shown in Figure 5-2, and the structure model of the SFG and lean concrete backfill, as shown in Figure 5-3.

The SASSI model for the NI structures has the following attributes:

Total number of nodes	=	32,778
Total number of interaction nodes	=	9,254
Total number of solid elements	=	35,113
Total number of shell elements	=	17,976
Total number of beam elements	=	4,039
Total number of spring elements	=	1,906

SASSI model data are coded using the Fast Solver Version of the ACS-SASSI computer program (Reference 15).

5.3 Seismic Input Motions for SSI Analysis

The seismic input to the SASSI model of the NI structures is the statistically independent, three-component (H1, H2, and VT) set of CSDRS-compatible design acceleration time histories. The seismic input is prescribed at the control motion elevation for the APR1400 standard plant, which is at ground surface El. 98'-8".

The horizontal H1 and H2 time histories are input in the global X (E-W) and Y (N-S) directions, respectively, and the vertical VT time history is input in the global z (vertical) direction.

5.4 Seismic SSI Analysis Cases

To provide the seismic response parameters needed for the design of the APR1400 NI structures, seismic SSI analyses are performed for a total of twenty (20) cases. The twenty cases include ten (10) uncracked concrete stiffness cases for the nine (9) generic site profiles, designated as Cases S1U through S9U, plus a fixed-base analysis case designated Case S10U. The remaining ten (10) cases include ten (10) cracked concrete stiffness cases for the same nine (9) generic site profiles, designated as Cases S1C through S9C plus a fixed-base analysis case designated as Case S10C. The twenty (20) SASSI analysis cases are summarized in Table 5-3.

For each of the twenty (20) SSI analysis cases, an SASSI analysis is performed for the three directions of seismic input: (a) horizontal E-W direction with the seismic input of the H1 time history, (b) horizontal N-S direction with the seismic input of the H2 time history, and (c) vertical direction with the seismic input of the VT time history. Thus, sixty (60) SASSI analyses are conducted to generate the seismic response parameters needed for the design.

Because of the different seismic-wave-passage cut-off frequencies and the different SSI system frequencies for each site profile case considered, the number of frequencies within the seismic-wave-passage cut-off frequency used for each SASSI analysis case varies. The total number of frequencies analyzed for the analysis cases are summarized in Table 5-4.

6.0 SEISMIC ANALYSIS RESULTS

Results of the SASSI analyses for the SSE obtained from the twenty (20) analysis cases described in Subsection 5.4 are post-processed to generate the maximum seismic response parameters of interest for the design. The response parameters consist primarily of maximum structural forces and moments, in-structure response spectra (ISRS), maximum displacements relative to free field and basemat, and maximum seismic response accelerations. Post-processing procedures used to generate such maximum seismic response parameters and summaries of results generated from the post-processing are presented in this section.

The seismic response parameters described above are, in general, generated for each of the twenty (20) analysis cases considered. The results of all twenty (20) analysis cases are then enveloped to produce the twenty-analysis-cases-enveloped seismic response parameters.

Because the SASSI analyses for each analysis case are performed separately for the three directions (E-W, N-S, and vertical) of seismic input, the maximum seismic response parameters of interest are first generated from the results of SASSI analyses obtained for the individual direction of seismic input. Then, the maximum seismic response parameters of interest due to the combined three directions of seismic input are combined using the square-root-of-the-sum-of-squares (SRSS) combination rule.

6.1 Structural Response Forces and Moments

The maximum seismic global building response structural forces (axial and shear forces) and moments (torsional and overturning moments) are generated from the SASSI analysis results for the 10 cracked concrete stiffness analysis cases for use in the structural design. Because the SASSI models used in the analysis are finite element models, the procedure for generating the maximum global building response forces and moments for each of the 10 cracked concrete stiffness analysis cases follows the post-processing steps described below.

(1) For the building forces and moments at a specific elevation, designated by the symbol *"l"*, of a specific freestanding structure, designated by the symbol *"k"*, a cross-section of the structure *"k"* is made at the elevation *"l"*. The specific structure *"k"* for the RCB represents one of the freestanding structures in the RCB, namely, the CS, PSW, and SSW of the IS. For the AB, which is a structurally integrated freestanding structure, the specific structure *"k"* refers to the AB structure itself.

(2) For the specific freestanding structure *"k"*, the mass sub-matrix, designated by the symbol $[m_{kl}]$, that is associated with the subset of nodal DOFs of the nodes in the SASSI FEM for the structure *"k"* above the cross-section *"l"*, is generated from the SASSI mass matrix $[m]$ for the NI structures.

(3) The SASSI analysis results can be expressed in terms of a vector of absolute acceleration transfer function for all nodal DOFs in the SASSI FEM for the NI structures, computed at a specific calculated frequency "f_j", due to the seismic input direction *"p"*, *p* = X (E-W), Y (N-S), and Z (vertical). This vector is designated by the symbol $\{H^a(f_j)\}_p$. Based on the vector $\{H^a(f_j)\}_p$, a

sub-vector of absolute acceleration transfer function, designated as $\left\{H_{kl}^{q}\left(f_{j}\right)\right\}_{p}$, can be extracted for the nodal DOFs of all nodes above the cross-section *"l"* in the structure *"k"*.

(4) The seismic response inertia load sub-vector associated with the nodal DOFs of all nodes above the structure cross-section *"l"* in the structure *"k"*, designated as $\left\{H_{kl}^{I}\left(f_{j}\right)\right\}_{p}$, can be computed by multiplying the mass sub-matrix $\left[m_{kl}\right]$ by the seismic inertia load sub-vector $\left\{H_{kl}^{I}\left(f_{j}\right)\right\}_{p}$, i.e.,

$$\left\{H_{kl}^{I}\left(f_{j}\right)\right\}_{p} = \left[m_{kl}\right] \left\{H_{kl}^{I}\left(f_{j}\right)\right\}_{p} \qquad (6\text{-}1)$$

(5) The transfer function of seismic response building (axial or shear) force in the direction *"q"*, *q* = X (E-W), Y (N-S), and Z (vertical), due to seismic input in direction *"p"*, *p* = X, Y, and Z, designated by the symbol $V_{kl}^{q}\left(f_{j}\right)_{p}$, can be computed by multiplying the seismic response inertia load sub-vector $\left\{H_{kl}^{I}\left(f_{j}\right)\right\}_{p}$ by a rigid-body translation sub-vector in direction *"q"* due to seismic input in the direction *"p"*, designated as $\left\{R_{kl}^{q}\right\}_{p}$, i.e.,

$$V_{kl}^{q}\left(f_{j}\right)_{p} = \left\{R_{kl}^{q}\right\}_{p}^{T} \left\{H_{kl}^{I}\left(f_{j}\right)\right\}_{p} \qquad q = \text{X, Y, Z} \qquad (6\text{-}2)$$

where $\left\{R_{kl}^{q}\right\}_{p}^{T}$ is the transpose of the sub-vector $\left\{R_{kl}^{q}\right\}_{p}$. The sub-vector $\left\{R_{kl}^{q}\right\}_{p}$ contains vector coefficients with the value 1 for each nodal DOF in the direction *"q"* and the value of 0 for all other DOFs.

(6) The transfer function of seismic response building (torsional or overturning) moment about the coordinate axis *"q"*, *q* = X, Y, and Z, due to seismic input in direction *"p"*, *p* = X, Y, and Z, designated by the symbol $M_{kl}^{q}\left(f_{j}\right)_{p}$, can be computed by multiplying the seismic response inertia load sub-vector $\left\{H_{kl}^{I}\left(f_{j}\right)\right\}_{p}$ by a rigid-body rotation sub-vector of moment arms r_{q}^{i} about the axis *"q"* between the nodal DOF *"i"* relative to a designated point *"o"* on the plane of the structure cross-section *"l"* due to the seismic input in the *p* direction, designated as $\left\{R_{\theta kl}^{\ q}\right\}_{p}$, i.e.,

$$M_{kl}^{q}\left(f_{j}\right)_{p} = \left\{R_{\theta kl}^{\ q}\right\}_{p}^{T} \left\{H_{kl}^{I}\left(f_{j}\right)\right\}_{p} \qquad q = \text{X, Y, Z} \qquad (6\text{-}3)$$

where $\left\{R_{\theta kl}^{\ q}\right\}_{p}^{T}$ is the transpose of the sub-vector $\left\{R_{\theta kl}^{\ q}\right\}_{p}$. The sub-vector $\left\{R_{\theta kl}^{\ q}\right\}_{p}$ contains vector coefficients with the moment arm r_{q}^{i} relative to the point *"o"* for each nodal translation DOF *"i"* rotating about the coordinate axis *"q"*, the value of 1 for all nodal rotation DOFs rotating about the axis *"q"*, and the value of 0 for all other DOFs.

(7) The structure force and moment transfer functions, $V_{kl}^{q}\left(f_j\right)_p$ and $M_{kl}^{q}\left(f_j\right)_p$, obtained from Eqs. (6-2) and (6-3) at each calculated frequency f_j, are interpolated and then convolved with the seismic input time history in the direction *"p"* to generate the time histories of building (axial and shear) forces and (torsional and overturning) moments. The maximum forces and moments, designated as $\left(V_{kl\,\max}^{q}\right)_p$ and $\left(M_{kl\,\max}^{q}\right)_p$ for the structure *"k"* at the structure cross-section *"l"* due to the seismic input in direction *"p"* are obtained as the maximum values of the time histories.

(8) The maximum structure forces and moments for the structure *"k"* at the structure cross-section *"l"* due to the seismic input in direction *"p"* obtained in Step (7) above are combined, using SRSS combination rule, to generate the maximum forces and moments due to the seismic inputs in all three directions.

(9) Steps (1) through (8) are repeated for all structure cross-sections of interest of all freestanding structures in the NI structures.

(10) From Step (2) described above, the total mass of the structure *"k"* above the structure cross-section *"l"* in the direction *"q"* due to seismic input in the direction *"p"*, designated as $\left(m_{kl}^{t}\right)_p^q$, can be computed from the mass sub-matrix $\left[m_{kl}\right]$ and the rigid-body translation sub-vector $\left\{R_{kl}^{q}\right\}_p$, as defined in Step (5), as follows:

$$\left(m_{kl}^{t}\right)_p^q = \left\{R_{kl}^{q}\right\}_p^T \left[m_{kl}\right] \qquad p,\ q = X, Y, Z \qquad (6\text{-}4)$$

The tributary mass of the structure *"k"* between the structure cross-sections "(*l* -1)" and *"l"* in the direction *"q"* due to seismic input in the direction *"p"*, designated as $\left(\Delta m_{kl}^{t}\right)_p^q$, can be computed as

$$\left(\Delta m_{kl}^{t}\right)_p^q = \left(m_{kl}^{t}\right)_p^q - \left(m_{k(l-1)}^{t}\right)_p^q \qquad p,\ q = X, Y, Z \qquad (6\text{-}5)$$

(11) From Step (7), the differential maximum building structure (axial and shear) forces in the structure *"k"* above the structure cross-section *"l"* in the direction *"q"* due to seismic input in the direction *"p"*, designated as $\left(\Delta V_{kl\,\max}^{q}\right)_p$, can be computed from the maximum build forces computed at the cross-sections "(*l* -1)" and *"l"* as follows:

$$\left(\Delta V_{kl\,\max}^{q}\right)_p = \left(V_{kl\,\max}^{q}\right)_p - \left(V_{k(l-1)\max}^{q}\right)_p \qquad \text{p, q = X, Y, Z} \qquad (6\text{-}6)$$

(12) From the tributary mass $\left(\Delta m_{kl}^{t}\right)_p^q$, computed from Step (11) using Eq. (6-5), and the differential maximum building structure (axial and shear) forces $\left(\Delta V_{kl\,\max}^{q}\right)_p$, computed from Step (11) using Eq. (6-6), the equivalent seismic response acceleration, designated as $\left(a_{kl}\right)_p^q$, of the structure *"k"*

between the cross-sections "(*l* -1)" and *"l"* in the direction *"q"* due to seismic input in the direction *"p"*, can be derived as follows:

$$\left(a_{kl}\right)_p^q = \left(\Delta V_{kl\,\max}^q\right)_p / \left(\Delta m_{kl}^t\right)_p^q \qquad p, q = X, Y, Z \qquad (6\text{-}7)$$

The equivalent acceleration $\left(a_{kl}\right)_p^q$ computed from Eq. (6-7) is the acceleration to be used for structural design. The application of the equivalent acceleration so derived will produce the maximum seismic response building (axial and shear) forces computed from Step (7) described above.

Following the steps described above, the maximum building seismic response (axial and shear) forces and (torsional and overturning) moments, along with the equivalent maximum seismic response accelerations derived from the maximum building seismic response forces for structural design, are computed at various designated elevations for the RCB (CS, PSW, and SSW) and AB. The results of each of the ten (10) cracked-concrete SASSI analysis cases and the envelopes of the results for the ten (10) cases are tabulated and plotted in Appendix C of this report.

The calculations of the maximum building seismic response forces and moments described above have included all building masses except the RCS masses and the convective (sloshing) hydrodynamic masses for the first and second horizontal sloshing modes of IRWST and the horizontal sloshing mode of AFW and FHA tanks. Thus, for the structural design, the maximum seismic response RCS support reaction forces and moments and the maximum hydrodynamic pressures generated from the maximum seismic response of the horizontal sloshing modes of IRWST, AFW and FHA tanks are added to the maximum building seismic response forces and moments that are computed.

6.2 In-Structure Response Spectra

The SASSI analysis output-acceleration-response time histories obtained for each analysis case at selected nodal points of the SASSI FEM on the designated elevations of RCB (i.e., CS, PSW, and SSW) and AB are used to compute the ISRS. The ISRS are computed for constant spectral damping values of 2, 3, 4, 5, 7, and 10%.

The selected nodal points on each of the designated structure elevations in the RCB are summarized in five tables: Table 6-1 for the CS, Table 6-2 for the polar crane at El. 241'-0" of the CS, Table 6-3 for PSW, Table 6-4 for SSW, and Table 6-5 for the slabs in the RCB for the vertical slab response only. The selected nodal points on each designated floor area of each designated floor elevation in the AB are summarized in Tables 6-6 and 6-7. Table 6-6 lists the selected nodal points on each designated floor area at the shear wall locations of each designated floor elevation for which ISRS for seismic response motions in all three directions, X (E-W), Y (N-S), and Z (vertical), are generated. Table 6-7 lists the selected nodal points on the floor slabs of each designated floor area of each designated floor elevation for which ISRS for the vertical (Z) seismic response motions are generated. The locations of the selected nodes on the designated elevations are shown on plots in Appendix D of this report.

The ISRS generated for each analysis case at all selected nodal points on each designated structure elevation are first enveloped to generate the enveloped ISRS for the elevation and are then widened by ±

15% in frequency. The enveloped and widened ISRS for each elevation generated for all six constant damping values are generated for each individual SASSI analysis case. The ISRS generated are finally enveloped for all twenty (20) cases. The ISRS curves that are generated are plotted in the figures shown in Appendix E.

6.3 Maximum Seismic Response Relative Displacements

Two sets of maximum seismic response relative displacements are generated for the RCB and AB from the SASSI analysis results for all twenty (20) SASSI analysis cases. The first set consists of the displacements relative to the free-field ground surface. The second set consists of the displacements relative to the basemat. For the RCB, the second set consists of the displacements relative to the region of basemat under the RCB footprint. Because of the massive concrete pedestal in the lower portion of the internal structure, the basemat under the RCB footprint is rigid and responds almost as a rigid basemat. Thus, the second set of displacements relative to the basemat is obtained from the first set of relative displacements with respect to the free-field ground surface by removing the rigid basemat rotations computed for the region of basemat under the RCB footprint. For the AB, the second set of displacements relative to the basemat is obtained from the first set of relative displacements with respect to the free-field ground surface by subtracting the basemat displacements at the containment centerline relative to the free-field ground surface from the first set of relative displacements.

For the first set of relative displacements, which are displacements relative to the free-field ground surface, the post-processing procedure used to generate these displacements for the selected nodal points on the designated structure elevations are as follows:

(1) For each selected nodal point *"i"* on each designated structure elevation *"l"*, the acceleration response transfer function computed at a calculated frequency f_j in the *"q"* direction due to the seismic input in the *"p"* direction, designated by the symbol $\left(H^a\left(f_j\right)\right)_p^q$, is used to compute the transfer function of displacement relative to the free-field ground surface, designated by the symbol $\left(H^d\left(f_j\right)\right)_p^q$, using the following equation:

$$\left(H^d\left(f_j\right)\right)_p^q = -\left(\left(H^a\left(f_j\right)\right)_p^q - 1\right) \;/\; \left(2\pi f_j\right)^2 \qquad \text{(6-8)}$$

The computed relative displacement transfer function $\left(H^d\left(f_j\right)\right)_p^q$ at the calculated frequencies is then interpolated and convolved with the seismic input acceleration time history to obtain the time history of displacement relative to the free-field ground surface in the *"q"* direction due to the seismic input in the *"p"* direction, designated by $d_p^q(t)$.

(2) The maximum displacement in the *"q"* direction relative to the free-field ground surface due to the seismic input in the *"p"* direction, designated as $d_{p\,\max}^q$, is obtained as the maximum absolute value of the time history $d_p^q(t)$. The maximum relative displacement in the *"q"* direction due to the

seismic input in all three directions, i.e., *p* = X, Y, Z, designated by the symbol $d^q_{\max}$, is obtained by combining the maximum relative displacements due to the inputs in all three directions using the SRSS combination rule, i.e.,

$$d^q_{\max} = \sqrt{\left(d^q_{X\max}\right)^2 + \left(d^q_{Y\max}\right)^2 + \left(d^q_{Z\max}\right)^2} \qquad (6\text{-}9)$$

(3) The maximum relative displacement $d^q_{\max}$ obtained from Eq. (6-9) for all selected nodes *"i"* on a designated elevation *"l"* in the structure *"k"* are enveloped to generate the enveloped maximum relative displacement in the direction *"q"*.

The enveloped maximum relative displacements generated from Step (3) above for all designated elevations in the RCB and AB for each of the twenty SASSI analysis cases are tabulated in Appendix F.

To remove the rigid RCB basemat rotation from the displacements relative to the free-field ground surface, the basemat rotation about a global coordinate axis *"p"*, *p* = X or Y, located at the center of the containment on top of the basemat, designated as point *"o"*, is computed first. The basemat rotation is calculated using the following steps:

(1) Two points designated as A and B on top of the basemat in the orthogonal direction to the coordinate axis *"q"* with the horizontal distance "D" between A and B are selected. The transfer functions of the vertical displacements at points A and B at the calculated frequency f_j, designated as $H^d_Z\left(f_j\right)^A_q$ and $H^d_Z\left(f_j\right)^B_q$, can be computed using Eq. (6-8).

(2) The basemat rotation about the coordinate axis *"q"* due to seismic input in the direction *"p"*, designated by the symbol $R^p_{\theta q}\left(f_j\right)$, can be computed as follows:

$$R^p_{\theta q}\left(f_j\right) = \left[\ H^d_Z\left(f_j\right)^A_q - H^d_Z\left(f_j\right)^B_q\ \right] / \mathrm{D} \qquad (6\text{-}10)$$

(3) For a designated nodal point *"i"* on a designated structure elevation *"l"* with height h_l, the transfer function of displacement relative to the basemat, designated as $H^d_b\left(f_j\right)^q_p$, can be computed from the transfer function of displacement relative to the free-field ground surface $H^d\left(f_j\right)^q_p$ computed at frequency f_j as follows:

$$H^d_b\left(f_j\right)^q_p = H^d\left(f_j\right)^q_p - R^p_{\theta q}\left(f_j\right)\times h_l \qquad (6\text{-}11)$$

(4) The transfer function of displacement relative to the basemat $H^d_b\left(f_j\right)^q_p$ computed from Eq. (6-11) at calculated frequency f_j can be interpolated and convolved with the seismic input time history in the direction *"p"* to generate the response time history $d^q_{bp}(t)$, from which the maximum

absolute response value can be obtained, designated as $d_{bp\ \max}^{q}$. The maximum displacements relative to the basemat generated for the seismic input in all three directions can be combined using the SRSS combination rule to obtain the maximum displacements relative to the basemat due to all three directions of input, designated as $d_{b\ \max}^{q}$.

(5) The maximum displacements relative to the basemat $d_{b\ \max}^{q}$ generated for all nodal points on each designated elevation *"l"* are enveloped to give the enveloped maximum displacement relative to the basemat for the designated elevation for the response direction *"q"*.

The maximum displacements relative to the basemat obtained from Step (5) above for all designated elevations in the RCB are tabulated in Appendix F in a format that is similar to that for the maximum displacements relative to the free-field ground surface.

6.4 Maximum Seismic Response Accelerations

The maximum seismic response absolute accelerations obtained as the zero period acceleration (ZPA) values for the designated structure elevations in the RCB and AB, for twenty (20) individual SASSI analysis cases, are tabulated in Appendix G. The ZPA values tabulated for each designated elevation in the tables in Appendix H are the values enveloped of the ZPA values obtained for all selected nodes on that elevation.

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Table 2-1. APR1400 Certified Seismic Design Response Spectra – Horizontal

Damping Ratio (%)	Amplification Factor for Control Points						
	0.1 Hz	0.2 Hz	0.25 Hz	2.5 Hz	9 Hz	25 Hz	50 Hz
2	0.0276	0.111	0.171	1.275	1.062	0.511	0.300
3	0.0254	0.102	0.159	1.125	0.939	0.498	0.300
4	0.0238	0.096	0.147	1.020	0.852	0.487	0.300
5	0.0226	0.090	0.141	0.939	0.783	0.479	0.300
7	0.0207	0.084	0.129	0.816	0.681	0.464	0.300
10	0.0188	0.075	0.117	0.684	0.570	0.447	0.300

Table 2-2. APR1400 Certified Seismic Design Response Spectra – Vertical

Damping Ratio (%)	Amplification Factor for Control Points						
	0.1 Hz	0.2 Hz	0.25 Hz	3.5 Hz	9 Hz	25 Hz	50 Hz
2	0.0184	0.075	0.114	1.215	1.062	0.511	0.300
3	0.0170	0.069	0.105	1.074	0.939	0.498	0.300
4	0.0159	0.063	0.099	0.972	0.852	0.487	0.300
5	0.0151	0.060	0.093	0.894	0.783	0.479	0.300
7	0.0138	0.057	0.087	0.777	0.681	0.464	0.300
10	0.0125	0.051	0.078	0.651	0.570	0.447	0.300

Table 4-1. Dynamic Properties of Generic Soil/Rock Materials for Site Average-Shear-Wave-Velocity Categories P1 through P5

Average-Shear Wave-Velocity Categories	Average-Shear Wave-Velocity (ft/sec)	Soil/Rock Unit Weight (lb/ft^3)	Poisson's Ratio (ν)	Degradation Curve type (EPRI)
P1	1,200	125	0.40	Sand
P2	2,000	130	0.38	Sand
P3	4,000	135	0.35	Soft Rock
P4	6,000	145	0.33	Rock
P5	9,200	155	0.33	Rock

Table 4-2. Site Layering and Average-Shear-Wave-Velocity Categories Considered for Nine Generic Site Profiles

Layer Site Category Depth from Ground Surface (ft)	Generic Soil Profile No.								
	S1	S2	S3	S4	S5	S6	S7	S8	S9
	Average-Shear-Wave-Velocity No.								
A 0 ~ 50 ft	P1	P1	P2	P2	P3	P2	P2	P4	P4
B 50 ~ 100 ft	P1	P1	P2	P2	P3	P3	P3	P4	P4
C 100 ~ 200 ft	P1	P2	P2	P3	P4	P3	P4	P4	P5
D 200 ~ 500 ft	P2	P3	P3	P4	P4	P5	P5	P5	P5
E 500 ~ 1,000 ft	P3	P4	P5	P5	P5	P5	P5	P5	P5
F > 1,000 ft	P5	P5	P5	P5	P5	P5	P5	P5	P5

Table 4-3. Fundamental Horizontal Site Frequencies of Nine Generic Site Profiles Considered for APR1400

Generic Site Profile No.	Fundamental Horizontal Frequency (Hz)
S1	1.27
S2	1.81
S3	2.39
S4	3.42
S5	4.30
S6	5.71
S7	6.54
S8	8.59
S9	12.01

Table 5-1. Maximum Wave-Passage Frequencies of SASSI Site Models for Nine Generic Site Profiles Considered for APR1400

Generic Site Profile Case	Averaged Shear Wave Velocity For 98'-6" (30 m) Depth (ft/sec)	Average Soil Layer Thickness (ft)	Maximum Wave-Passage Frequency (Hz)
S1	1,191	11	21.7
S2	995	11	18.1
S3	2,188	11	39.8
S4	1,866	11	33.9
S5	4,257	11	77.4
S6	3,239	11	58.9
S7	2,801	11	50.9
S8	6,528	11	118.7
S9	4,796	11	87.2

Table 5-2. Material Properties of Lean Concrete

Material	Design Strength (psi)	Modulus of Elasticity (ksf)	Poisson's Ratio ν	Unit Weight γ (pcf)
Lean Concrete	2,000	367,000	0.17	137

Table 5-3. SASSI Analysis Case Identification

Concrete Stiffness Cases	Generic Site Profile Cases									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Uncracked	S1U	S2U	S3U	S4U	S5U	S6U	S7U	S8U	S9U	S10U
Cracked	S1C	S2C	S3C	S4C	S5C	S6C	S7C	S8C	S9C	S10C

Table 5-4. Total Number of Frequencies Analyzed and Highest Frequency Analyzed

Analysis Case	Uncracked Concrete Cases									
	S1U	S2U	S3U	S4U	S5U	S6U	S7U	S8U	S9U	S10U
Number of Frequencies Analyzed	71	70	94	89	116	109	103	117	116	117
Analysis Cut-off Frequency (Hz)	20.07	20.07	41.09	35.23	71.01	59.01	50.61	71.01	71.01	71.01
Analysis Case	Cracked Concrete Cases									
	S1C	S2C	S3C	S4C	S5C	S6C	S7C	S8C	S9C	S10C
Number of Frequencies Analyzed	70	70	94	89	116	109	103	117	116	117
Analysis Cut-off Frequency (Hz)	20.07	20.07	41.09	35.23	71.01	59.01	50.61	71.01	71.01	71.01

Table 6-1. Selected Nodal Points on Designated Structure Elevations of Containment Structure for Generation of ISRS

Elevation (ft.)	Identification	SASSI Node Numbers
78.00	CS base at interface with concrete pedestal	13663, 13704, 13694, 13699, 13679, 13674,13682
89.75	CS shell	16623, 16577, 16581, 16589, 16593, 16599, 16612, 16618
103.75	CS shell	19988, 20015, 20016, 20025, 20030, 20037, 20011, 19992
117.75	Top ring at lower personnel airlock	22008, 22035, 22039, 21995, 22005, 22020, 22013, 22021
123.62	CS shell	23504, 23512, 23511, 23539, 23531, 23530, 23510, 23503
131.56	CS shell	24933, 24948, 24979, 24983, 24961, 24943, 24966, 24935
159.75	Bottom ring at equipment hatch	28225, 28234, 28229, 28226, 28202, 28232, 27207, 28242
180.00	Top ring at equipment hatch and upper personnel airlock	29872, 29828, 29842, 29868, 29852, 29851, 29773, 29652
195.50	Top of thickened portion at equipment hatch	30897, 30910, 30895, 30912, 30931, 30879, 30927, 30926
215.96	CS shell	31554, 31556, 31580, 31584, 31542, 31555, 31588, 31548
241.00	Polar crane plane elevation	31860, 31845, 31852, 31788, 31786, 31828, 31885, 31824
254.50	CS spring line	31939, 31943,31968, 31931, 31949, 31969, 31941, 31974
274.49	Dome	32045, 32083, 32040, 32062, 32046, 32065, 32059, 32051
301.53	Dome	32242, 32237, 32245, 32248, 32238, 32220, 32206, 32225
328.42	Dome	32494, 32496, 32497, 32495
331.75	Dome apex	32522

Table 6-2. Selected Nodal Points on Designated Structure Elevations of Polar Crane at El. 241'-0" for Generation of ISRS

Elevation (ft.)	Identification	SASSI Node Numbers
241.00	Intersection of ring beam and main crane girders	31906,31840,31870,31831
241.00	Polar crane main girders at cross beams locations	31853,31871,31807,31805
241.00	Ends (stiffened) of main polar crane girders	31799,31869

Table 6-3. Selected Nodal Points on Designated Structure Elevations of Primary Shield Wall for Generation of ISRS

Elevation (ft.)	Identification	SASSI Node Numbers
66.00	4 corners at RV pit walls (bottom)	11362, 11363, 11368, 11371
78.00	4 corners at RV pit walls (top)	13581, 13585, 13586, 13595
100.00	Top of concrete pedestal	19674, 19341, 19665, 19354, 19194, 19275, 19375, 19265, 19189, 19168
106.50	Refueling pool walls	20363, 20255, 20352, 20265, 20367, 20333, 20285, 20198, 20300, 20256
114.00	Reactor pool walls & RV at bottom of hot and cold legs	21555, 21497, 21458, 21495, 21504, 21758, 21411, 21483, 21482, 21382,21551
130.00	Top of reactor massive concrete block	24815, 24817, 24842, 24819, 24672, 24665, 24658, 24806, 24719, 24778, 24785
136.50	-	25241, 25246, 25277, 25288, 25296, 25202, 25254
156.00	Operating deck	28097, 28124, 27764, 27264, 27607, 28039, 28007, 27886
191.00(a)	PSW top elevation	30362, 30316, 30351, 30305, 30333, 30357
191.00(b)	PZR corners	30307, 30352

Table 6-4. Selected Nodal Points on Designated Structure Elevations of Secondary Shield Wall for Generation of ISRS

Elevation (ft.)	Identification	SASSI Node Numbers
78.00	SSW at concrete pedestal bottom	13318, 13328, 13338, 13349, 13353, 13323, 13333, 13345
100.00 (a)	SSW at interface with the concrete pedestal top	19698, 19712, 19334, 19724, 19719, 19705, 19717, 19729
78 - 100.00 (b)	IRWST tank walls	13270,13299,19263, 19239, 17151, 15192, 17196, 15387, 17160, 15201
106.50	Reactor pool walls	20383, 20181, 20182, 20395, 20389, 20185, 20175, 20399
114.00	Refueling pool walls	21613, 21385, 21642, 21632, 21621, 21751, 21766, 21636
130.00	Top of the massive concrete block	24610, 24752, 24720, 24631, 24618, 24814, 24695, 24640
136.50	-	25193, 25280, 25249, 25205, 25199, 25273, 25293, 25219
156.00	Operating deck	27225, 27761, 27280, 27466, 27387, 27237, 27224, 27768
191.00	Top elevation of SSW	30301, 30323, 30331, 30298, 30299, 30341

Table 6-5. Selected Nodal Points on Designated Slabs in Reactor Containment Building for Generation of Vertical ISRS

Elevation (ft.)	Identification	SASSI Node Numbers
156.00	RCB slabs @ S-W corner (RV head storage)	27913, 27921, 27934
125.00	Top of slabs at RCB west side	23580, 23588, 23591, 23592
114.00	Slab supporting heavy fan (RCB west side)	21522 ,21525, 21527, 21529, 21530, 21541
111.00	Bottom of refueling pool (RCB east side)	21105, 21115, 21126, 21128, 21130, 21132
106.50	Bottom of reactor pool (RCB west side)	20210, 20211, 20219, 20220
100.00	Slab at pedestals of the reactor drain tank (RCB west side)	19616, 19623, 19626, 19632, 19634, 19638
66.00	RV pit slab (bottom)	11354, 11355, 11358, 11359

Table 6-6. Selected Nodal Points at Shear Wall Locations on Designated Floor Elevations of Auxiliary Building for Generation of ISRS

Floor Elevation	Floor Identification	SASSI Model Node Numbers
55'-0"	Basemat	10600, 10642, 10647, 10715, 10717, 10751, 10803, 10806, 10863, 10876, 10884, 10936, 10942, 10946, 11021, 11025
68'-0"	Intermediate Floor, Areas 2 & 4	11376, 11393, 11397, 11402, 11417, 11422, 11502, 11529, 11579, 11583, 11614, 11651, 11656, 11668, 11678, 11725, 11862, 11865
78'-0"	Intermediate Floor	12248, 12278, 12319, 12327, 12415, 12438, 12491, 12509, 12517, 12543, 12641, 12651, 12679, 12819, 12823, 12875
100'-0"	Ground Floor	18085, 18140, 18165, 18173, 18289, 18382, 18488, 18496, 18526, 18532, 18632, 18692, 18812, 18820, 18856, 18950
120'-0"	Second Floor	22101, 22273, 22385, 22453, 22467, 22511, 22593, 22599, 22636, 22687, 22767, 22805, 22846, 22914, 22951, 23082
137'-6"	Third Floor	25316, 25320, 25334, 25348, 25350, 25390, 25440, 25529, 25565, 25618, 25665, 25927, 25940, 25956
156'-0"	Fourth Floor	27250, 27256, 27273, 27281, 27453, 27474, 27546, 27660, 27666, 27739, 27791, 27791, 27804, 27817
174-'0"	Fifth Floor	29074, 29186, 29206, 29227, 29275, 29303, 29316, 29368, 29380, 29473, 29475, 29624, 29642
195'-0"	Sixth Floor Areas 1 and 3	30375, 30443, 30542, 30545, 30556, 30557, 30590, 30837
195'-0"	Main Control Room Roof	30399, 30403, 30680
216'-9"	Roof at Area 2	31592, 31626, 31632
213'-0"	Penthouse Roof at Areas 1 & 3	31235, 31241, 31256
213'-6"	Fuel Handling Area	31421, 31470, 31519, 31525
195'-0"	Sixth Floor Area 2, Fuel Handling Area	30369, 30536, 30754, 30762, 30854
100'-0"	Ground Floor Area 2, Fuel Handling Area	18680, 18914, 18974
114'-0"	Intermediate Floor Area 2, Fuel Handling Area	21680, 21693, 21770
120'-0"	Second Floor Area 2, Fuel Handling Area	22818, 22824, 23108
137'-6"	Third Floor Area 2, Fuel Handling Area	25514, 25516, 25623
156'-0"	Fourth Floor Area 2, Fuel Handling Area	27432, 27838, 28027

Table 6-7. Selected Nodal Points on Floor-Slab Panels on Designated Floor Elevations of Auxiliary Building for Generation of Vertical ISRS

Floor Elevation	Floor Slab Identification	SASSI Model Node Numbers
55'-0"	Basemat	9501,9579,9604,9709, 9743,9861,9905
68'-0"	Intermediate Floor, Upper Basemat, Area 2&4	11454,11486,11430, 11448,11509,11520, 11527,11791,11804, 11945,11947,11949, 11970,11987,11992
78'-0"	Upper Basemat	12325,12364,12398,12435,12448,12473, 12477,12497,12524,12529,12547,12608, 12687,12699,12713,12732,12746,12773, 12797,12817,12868,12885,12894,12898, 12929,12933,12955,12961,13014,13030, 13116,13122,13128,13156,13163,13175, 13184,13186,13203,13232,13244
100'-0"	Ground Floor	18163,18183,18187,18218,18264,18268,18302,18325,18378,18431,18460,18470,18557,18582,18603,18608,18638,18676,18680,18700,18702,18717,18750,18766,18796,18827, 18852,18871,18879,18913,18914,18944,18954,18974,18987,19024,19035,19039,19049,19051,19056,19062,19066,19068,19076,19095,19105,19111,19120,19133
120'-0"	Second Floor	22462,22483,22496,22518,22545,22559,22572,22585,22659,22669,22737,22764,22769,22776,22835,22881,22919, 22928,22936,22949,22968,22995,23024,23036,23063,23076,23080,23091,23119,23148,23180,23194,23237,23265
137'-6"	Third Floor	25423,25434,25523,25577,25583,25614,25616,25633,25650,25687,25715,25765,25783,25791,25794,25809,25815, 25821,25830,25841,25913,25936,25961,26010,26065,26082,26086,26089,26122,26125,26130,26135,26141,26168, 26169
156'-0"	Fourth Floor	27317,27325,27343,27423,27488,27516,27551,27582,27620,27656,27693,27750,27760,27779,27785,27798,27802, 27813,27822,27833,27880,27892,27895,27896,27904,27910,27926,27968,27974,27980,28020,28023,28036,28088, 28108,28119
174-'0"	Fifth Floor	29069,29086,29099,29137,29148,29235,29247,29250,29255,29294,29328,29363,29393,29411,29426,29494,29502,29541,29563, 2957129576,29580,29608
195'-0"	Roof at Area 1 & 3 Roof at Main Control Room	30367,30393,30416,30417,30550,30587,30597,30604,30621,30631,30651,30667,30771,30860,30597,30604
216'-9"	Roof at Area 2	31620,31647,31701
213'-0"	Penthouse Roof at Area 1 & 3	31294,31306
213'-6"	Fuel Handling Area Roof	31477,31527
195'-0"	Roof at Area 2	30462,30751
100'-0"	Ground Floor, Fuel Handling Area, Area 2	18676,18700,18913
114'-0"	Spent Fuel Pool Bottom Slab, Area 2	21699,21731,21738

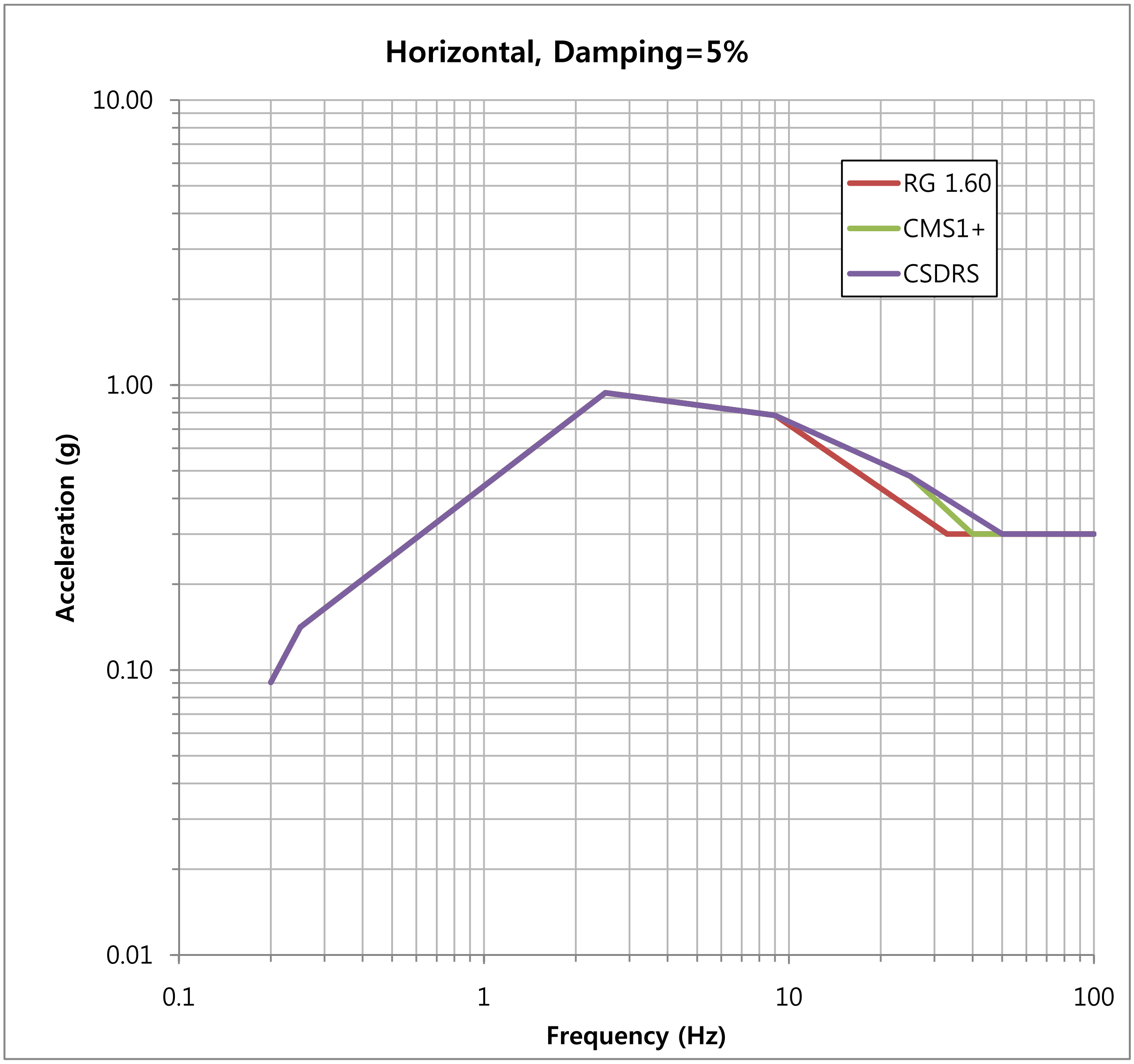

Figure 2-1. Comparison of 5%-Damped APR1400 CSDRS, CMS1+ DRS, and RG 1.60 DRS - Horizontal

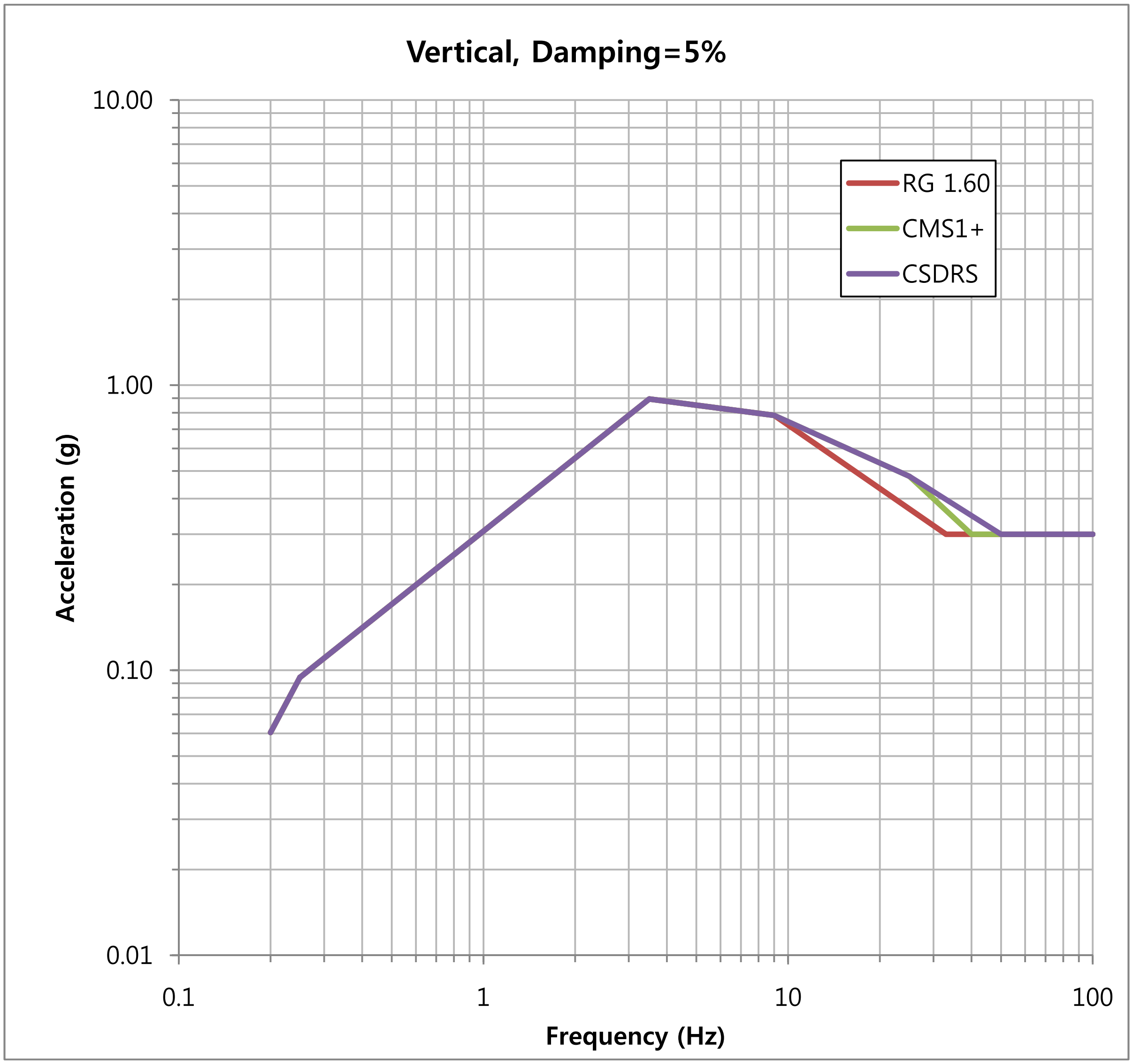

Figure 2-2. Comparison of 5%-Damped APR1400 CSDRS, CMS1+ DRS, and RG 1.60 DRS - Vertical

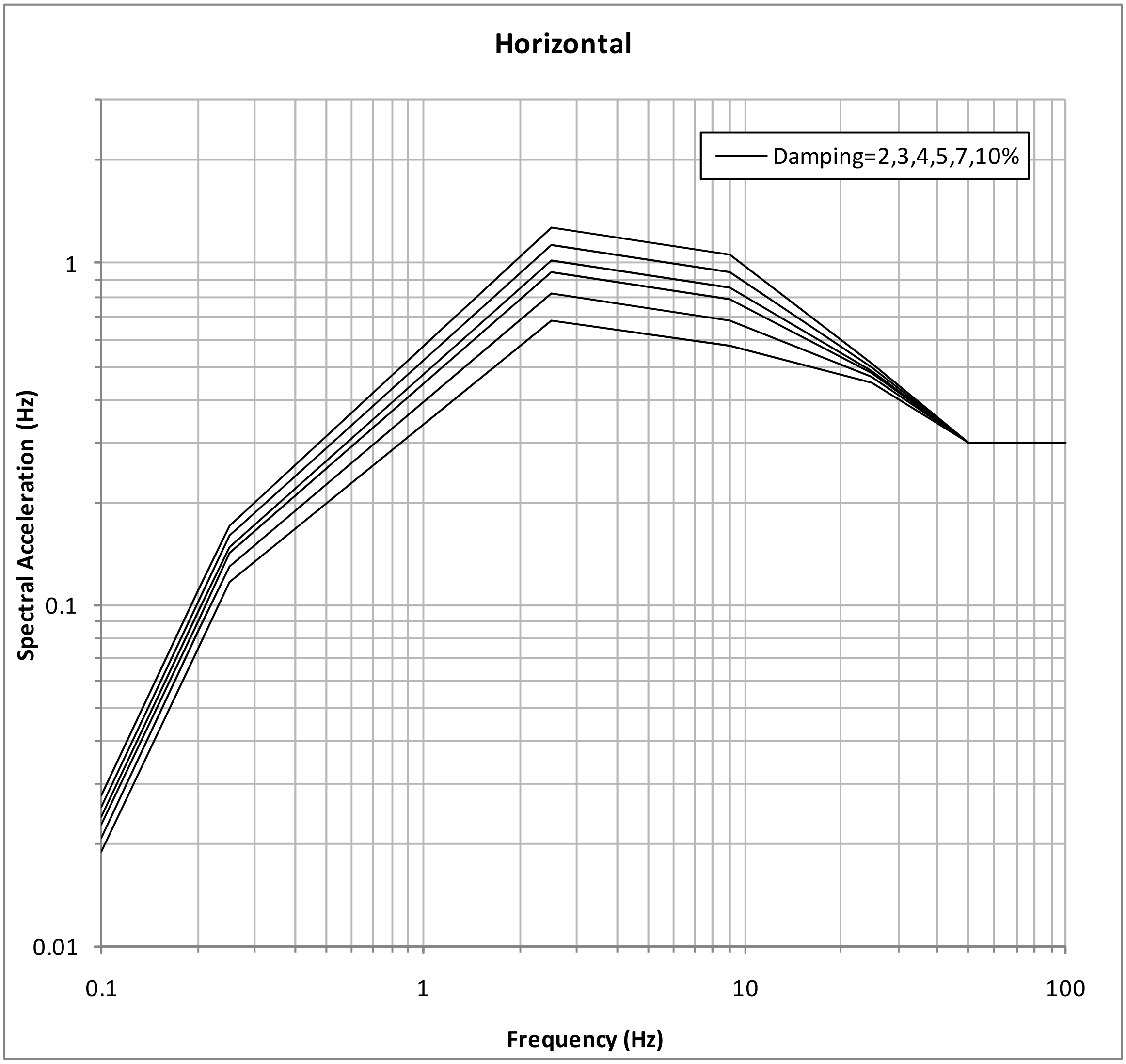

Figure 2-3. APR1400 Certified Seismic Design Response Spectra – Horizontal

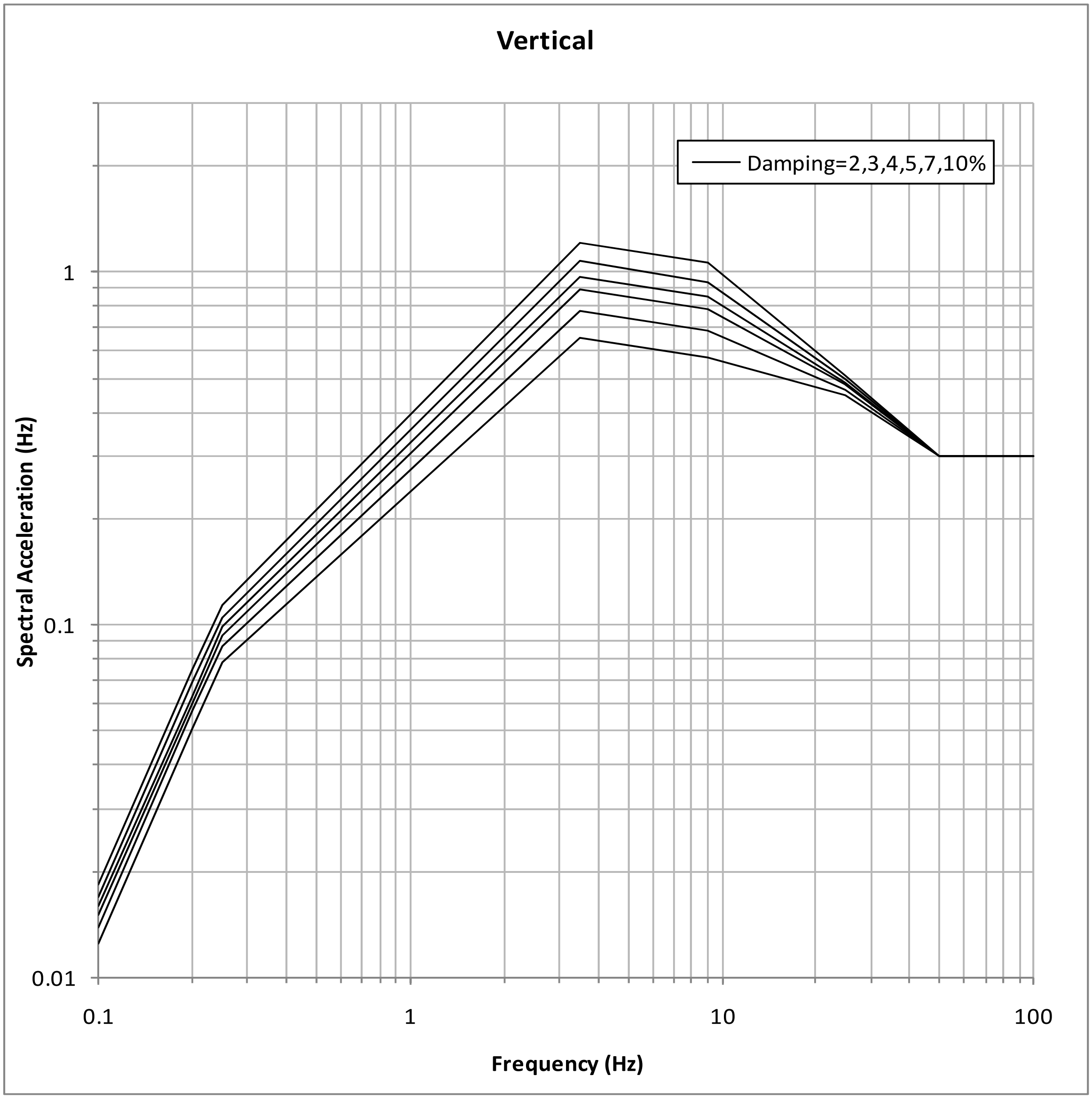

Figure 2-4. APR1400 Certified Seismic Design Response Spectra – Vertical

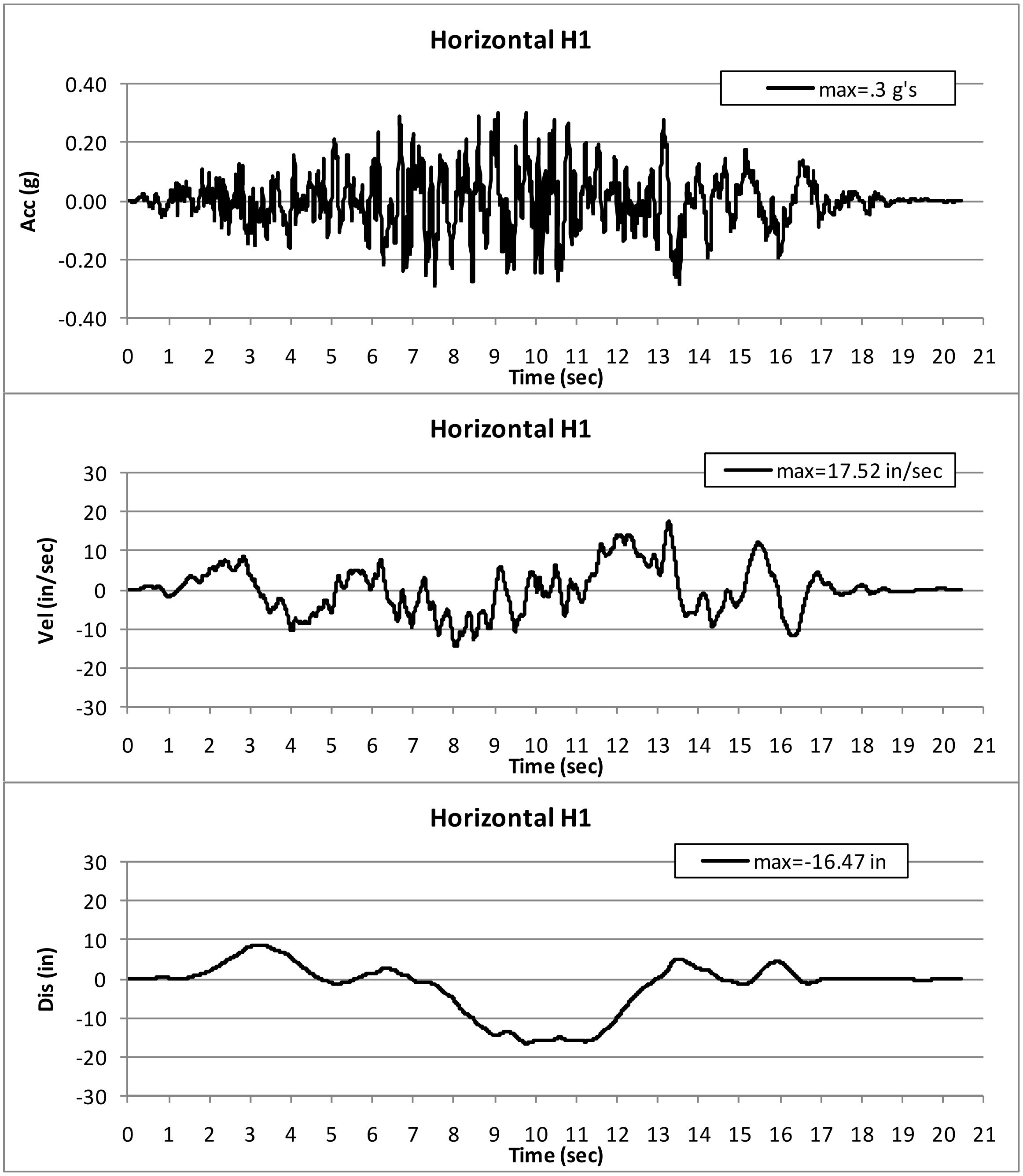

Figure 2-5. Generated CSDRS–Compatible Design Acceleration, Velocity, and Displacement Time Histories – Horizontal H1 Component

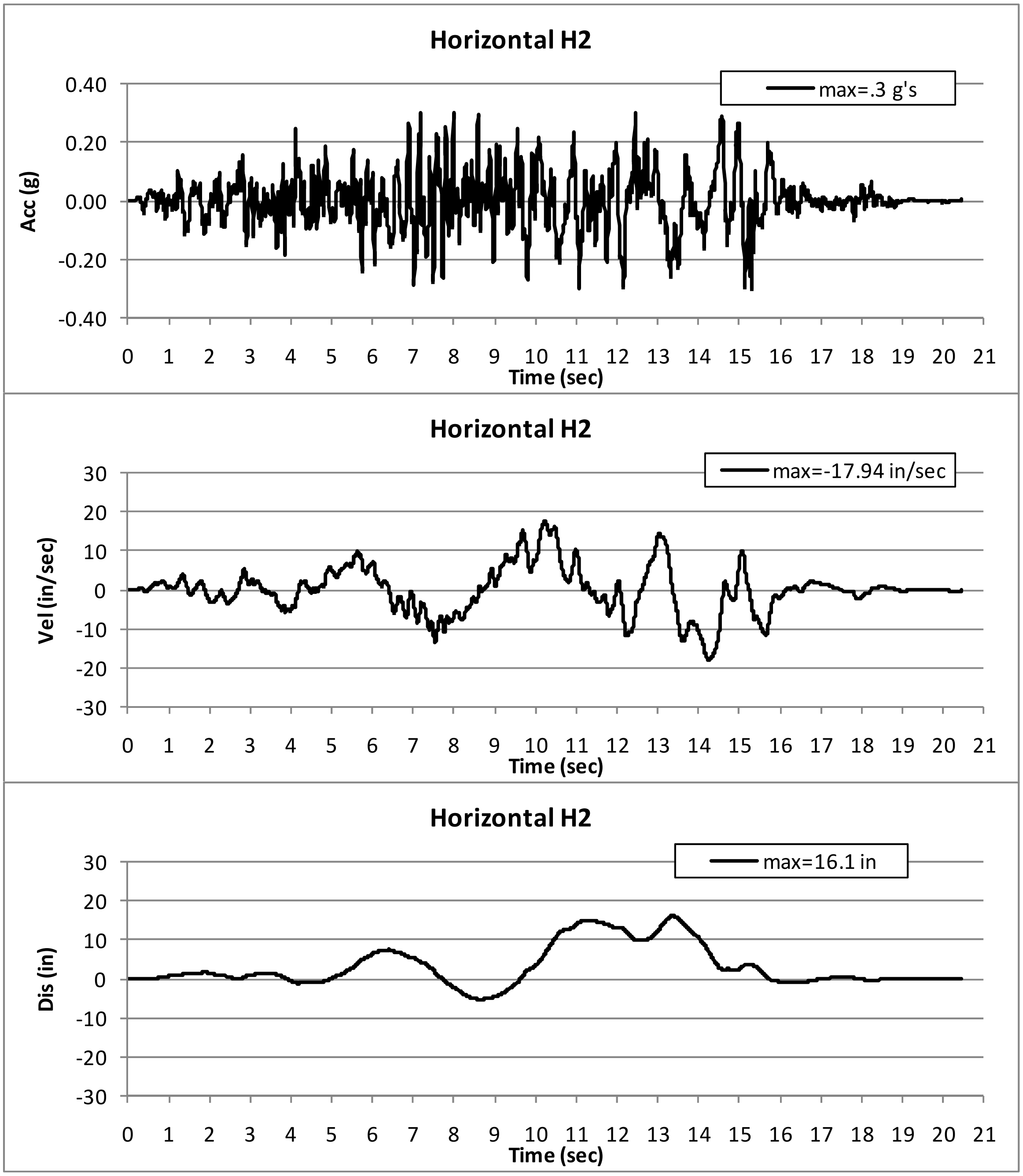

Figure 2-6. Generated CSDRS–Compatible Design Acceleration, Velocity, and Displacement Time Histories – Horizontal H2 Component

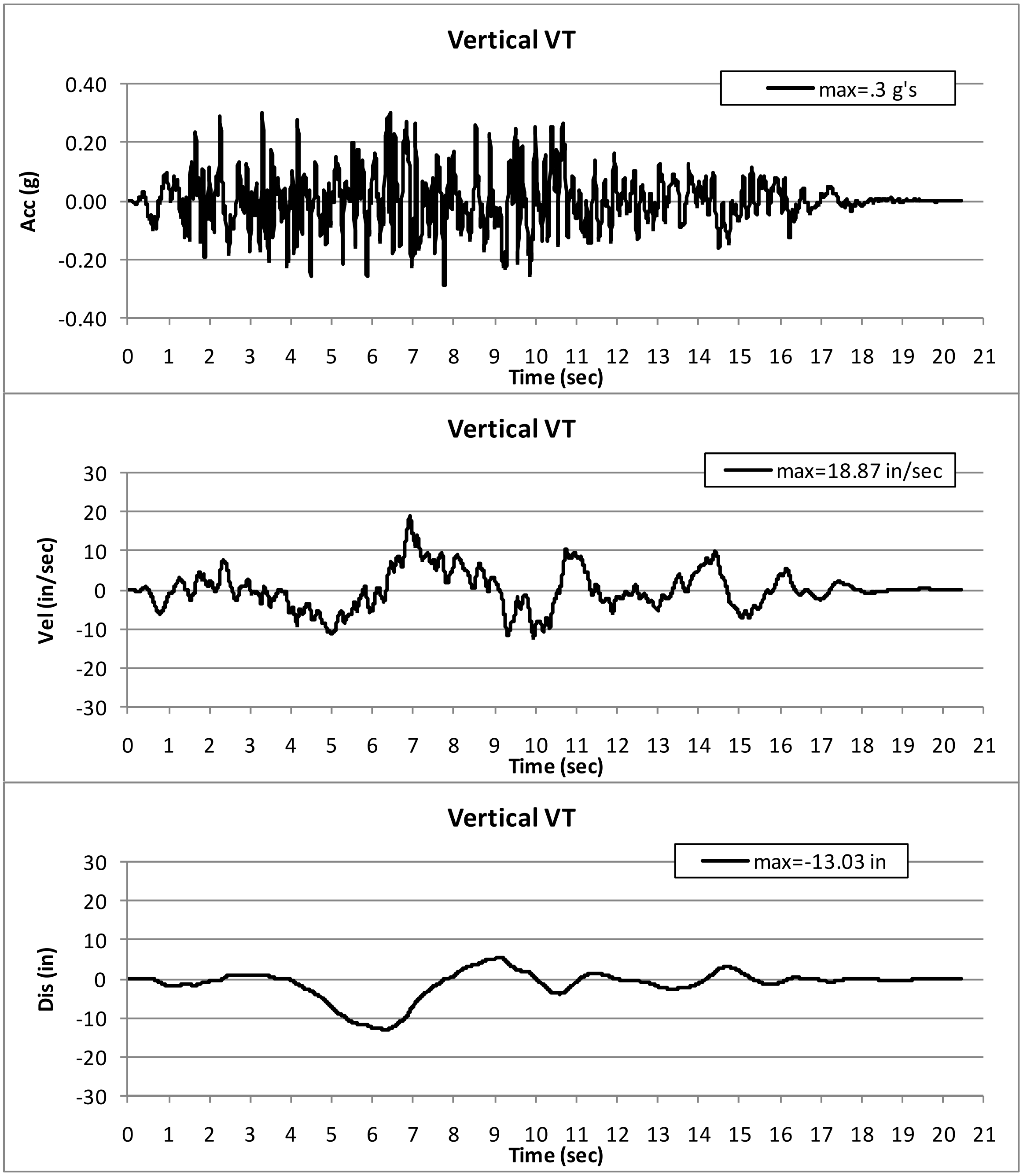

Figure 2-7. Generated CSDRS–Compatible Design Acceleration, Velocity, and Displacement Time Histories – Vertical VT Component

Security-Related Information – Withheld Under 10 CFR 2.390

Figure 3-1. Isometric View of Containment Structure

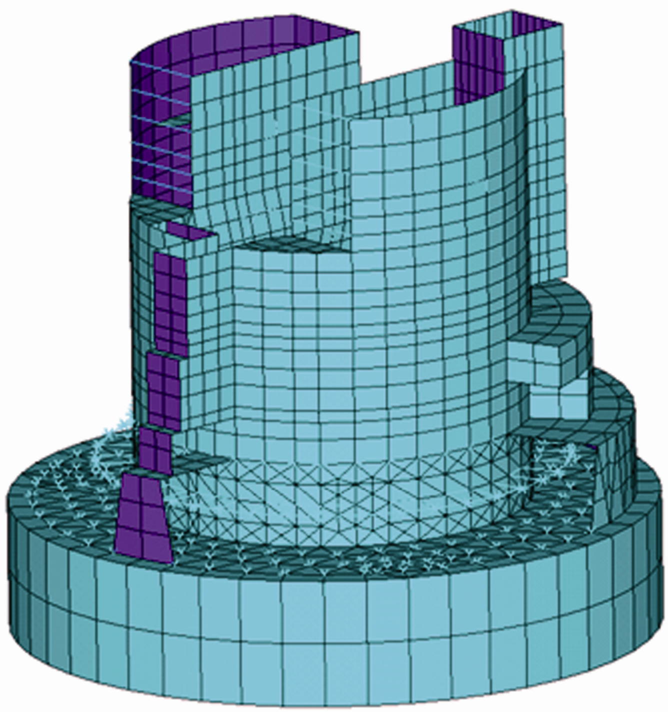

Figure 3-2. Isometric View of Internal Structure

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Figure 3-3. Reactor Coolant System Overview

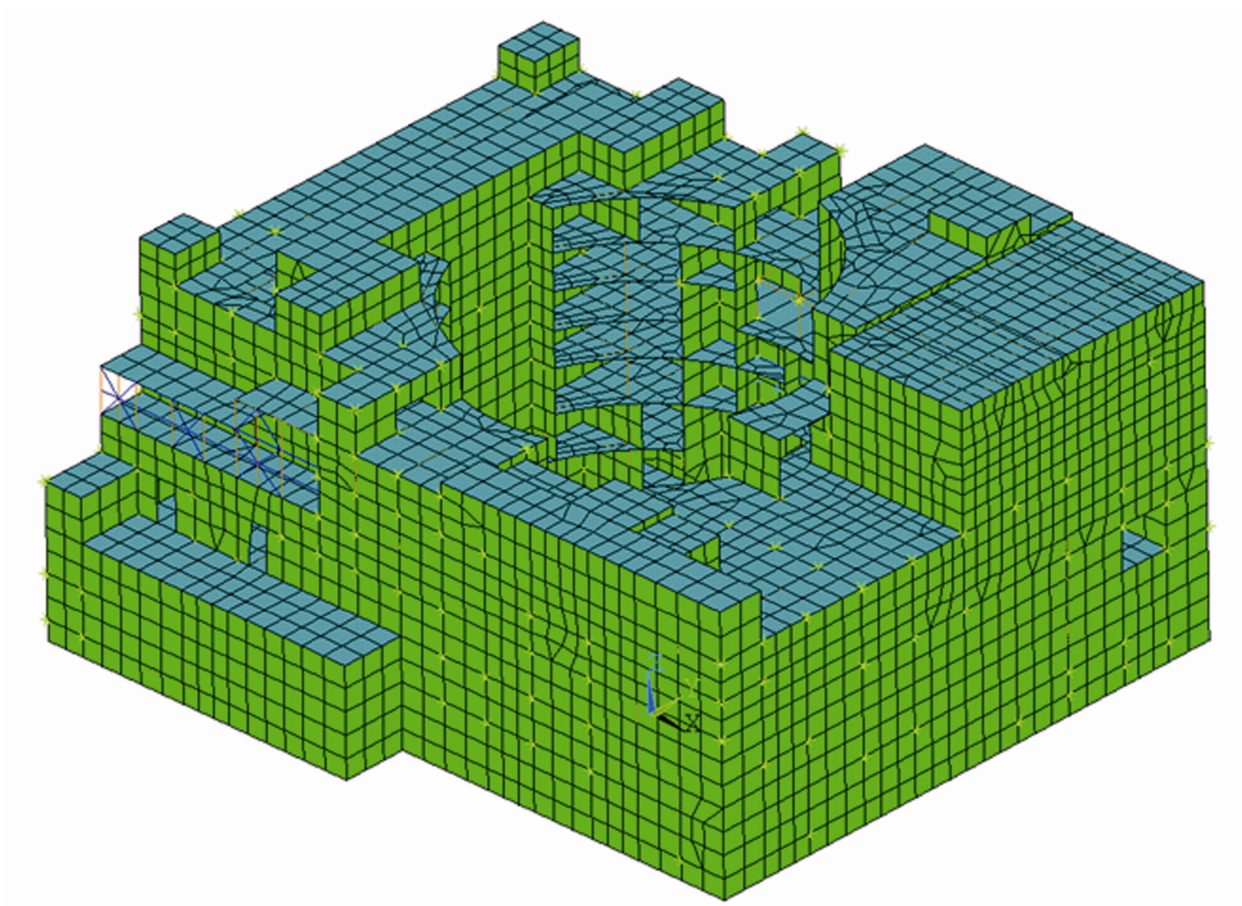

Figure 3-4. Isometric View of Auxiliary Building

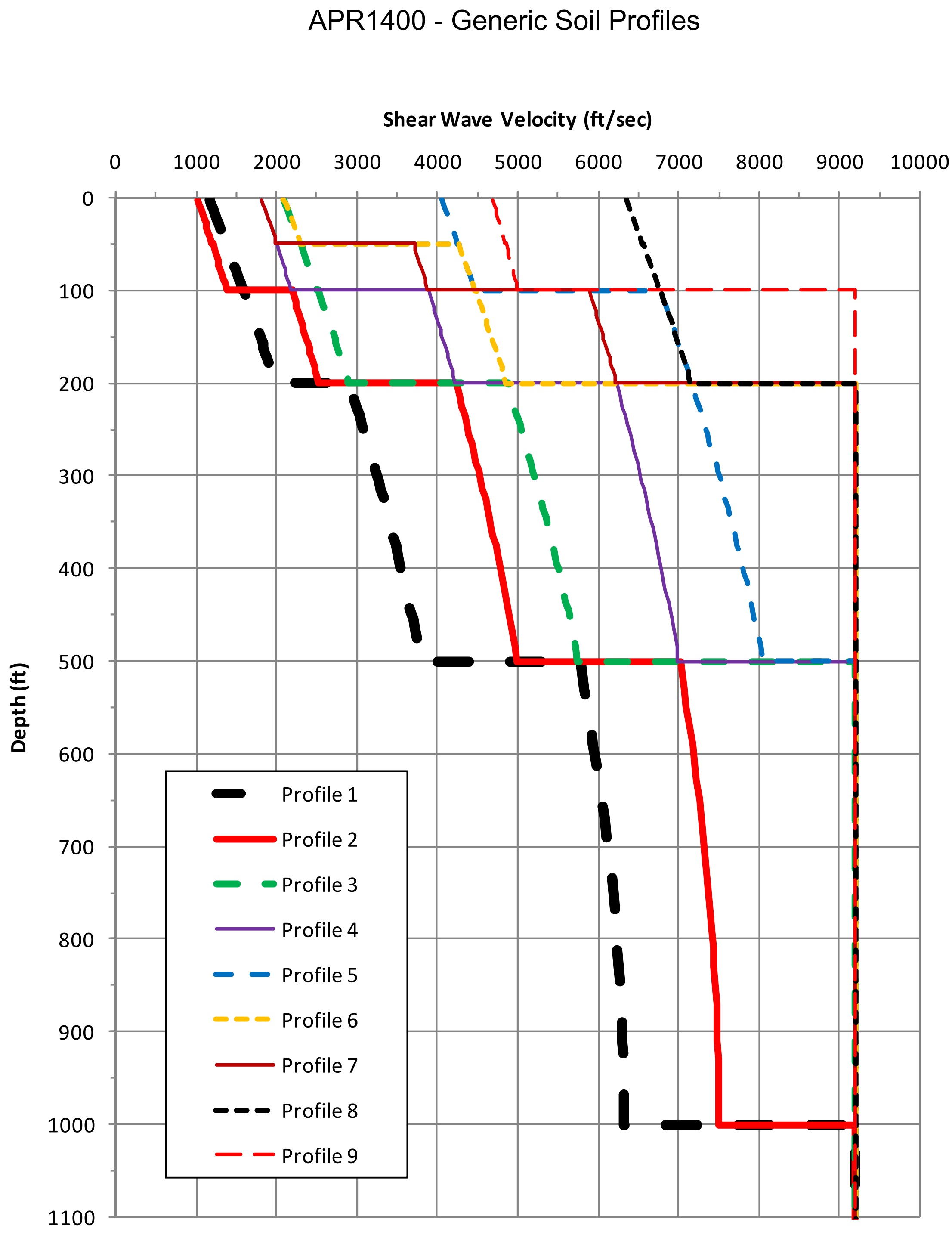

Figure 4-1. Low-Strain Shear Wave Velocity Profiles vs. Depth for Nine Generic Site Profiles Considered for APR1400

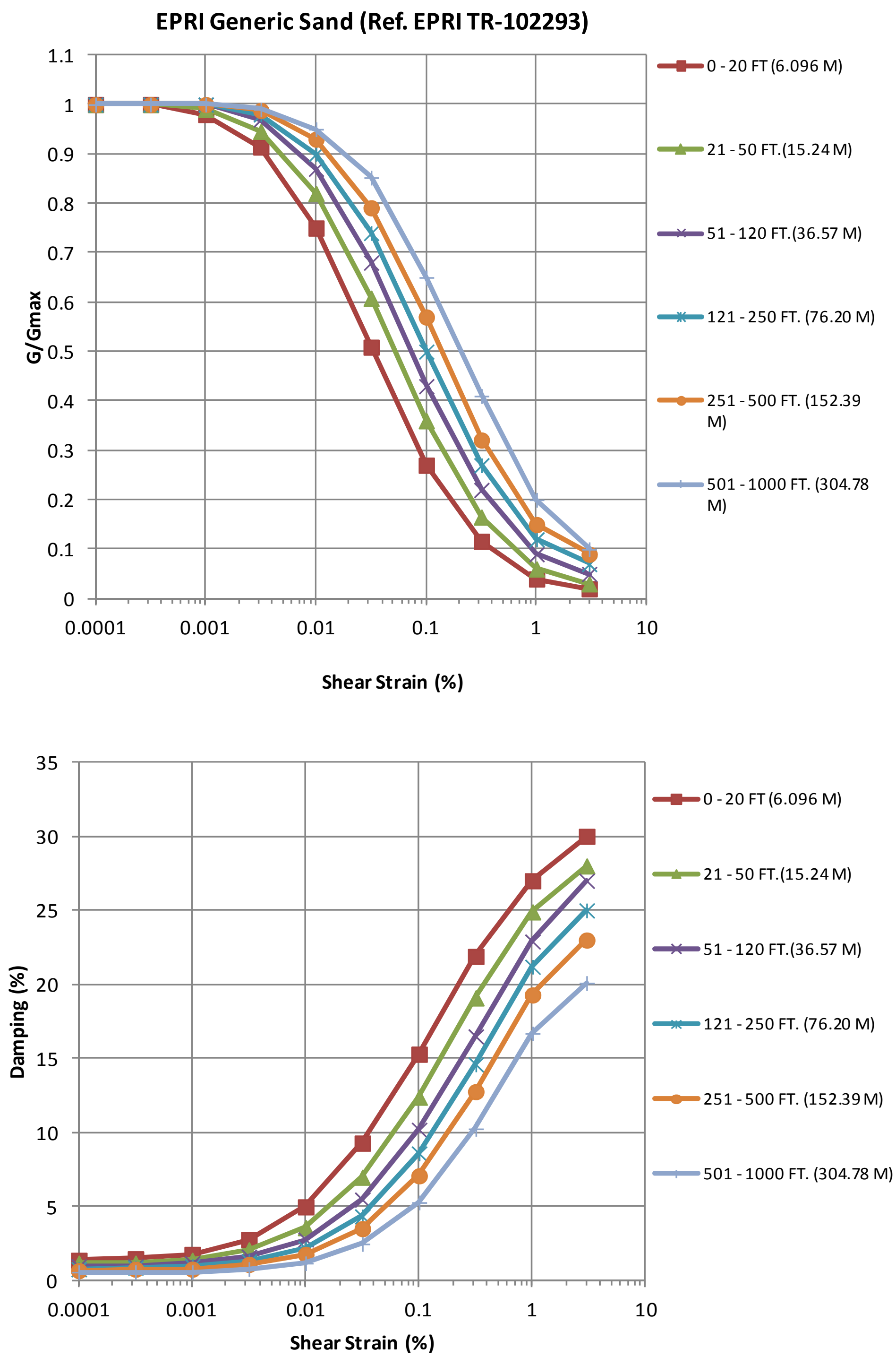

Figure 4-2. Shear-Modulus-Degradation and Damping-Value Variation Curves for Sand Considered for APR1400

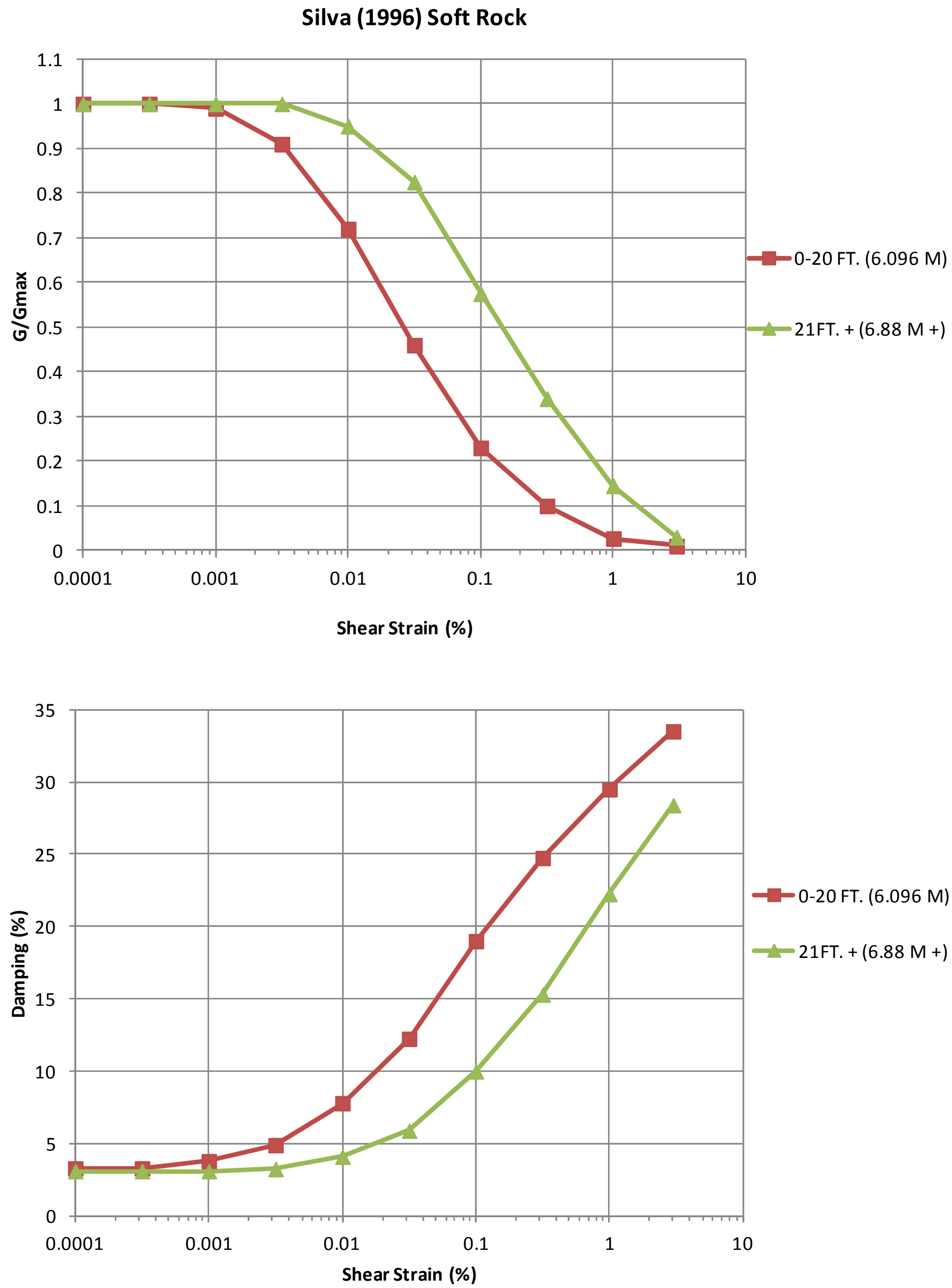

Figure 4-3. Shear-Modulus-Degradation and Damping-Value Variation Curves for Soft Rock Considered for APR1400

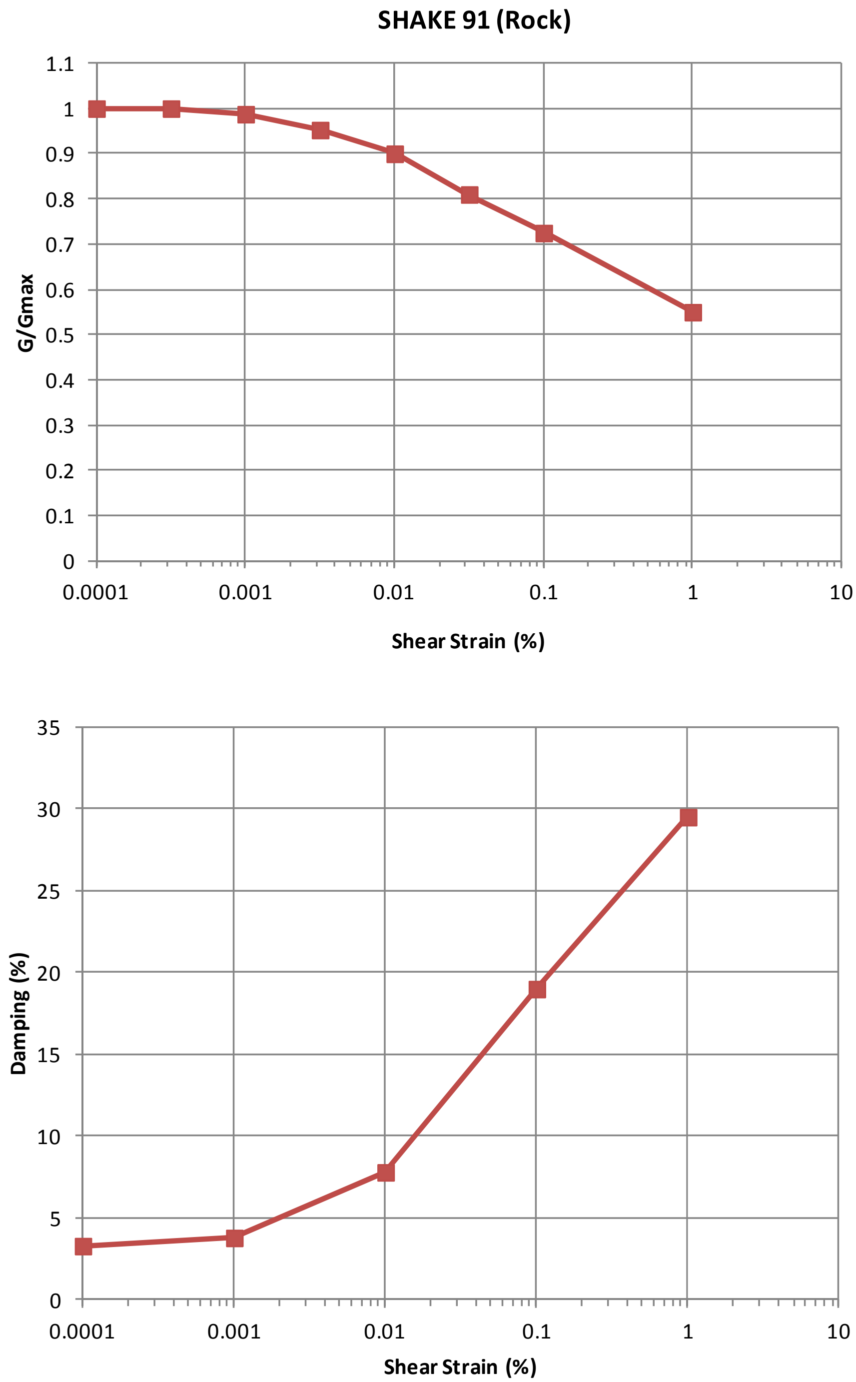

Figure 4-4. Shear-Modulus-Degradation and Damping-Value Variation Curves for Rock Considered for APR1400

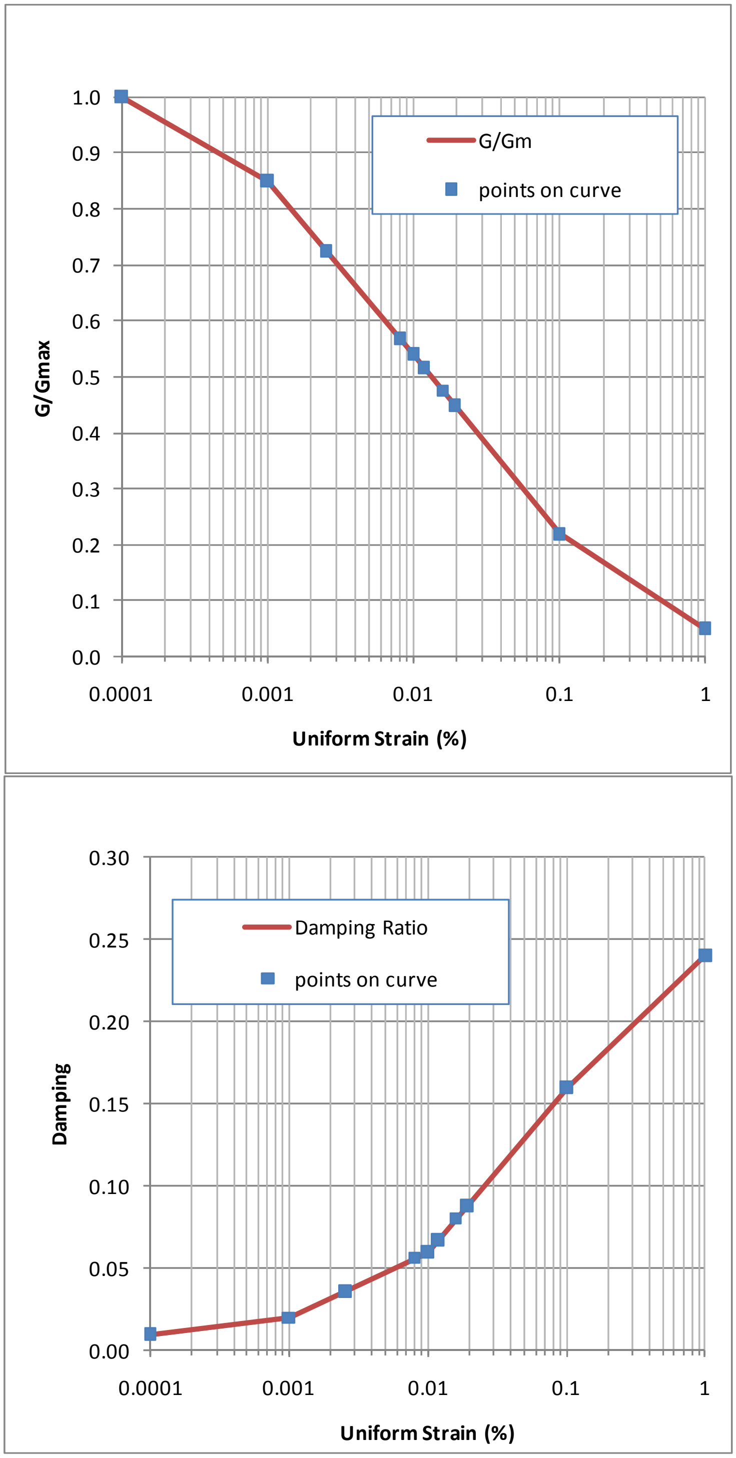

Figure 4-5. Shear-Modulus-Degradation and Damping-Value Variation Curves for Structural Fill Granular Considered for APR1400

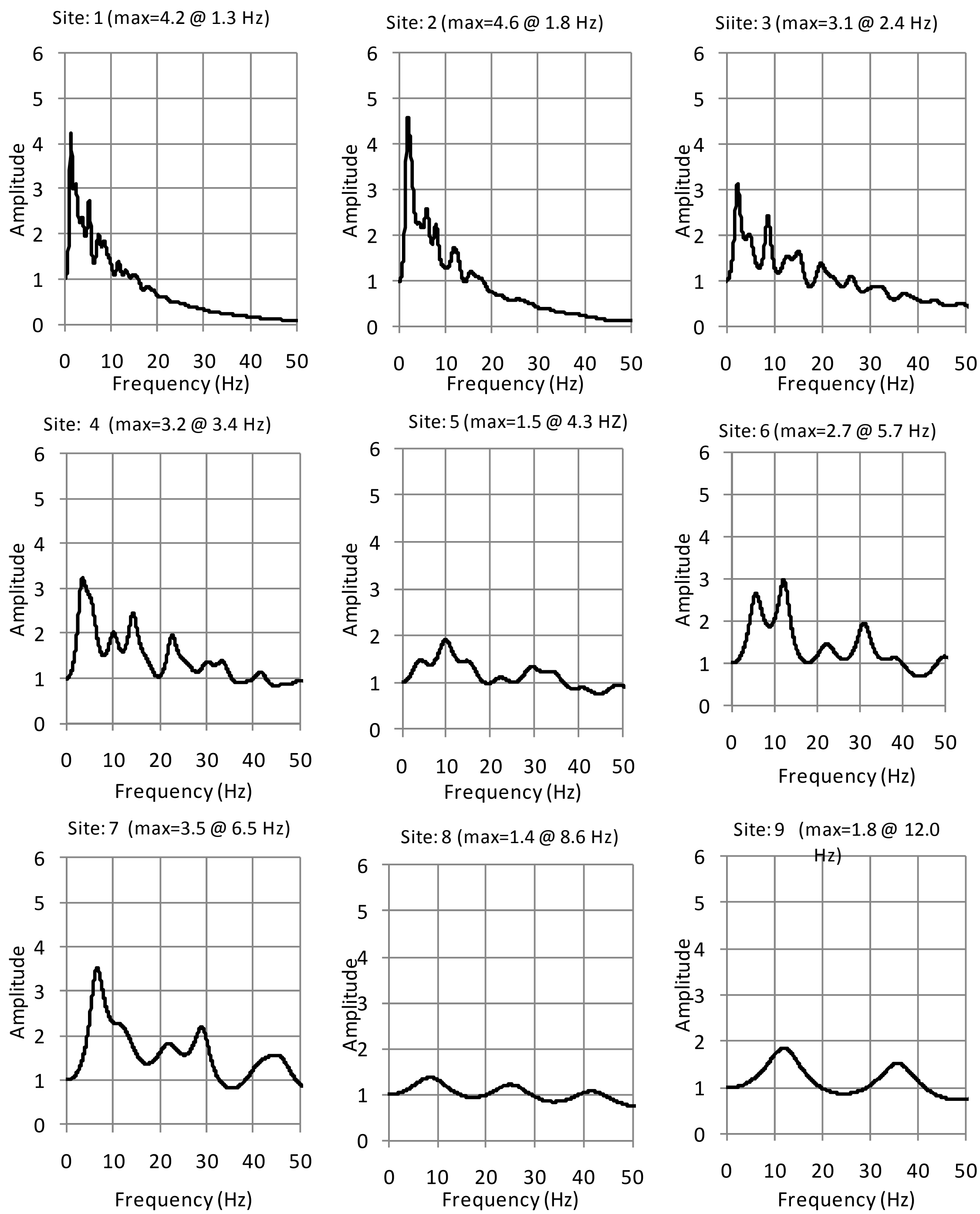

Figure 4-6. Horizontal Site Response Transfer Functions of Surface Motion Relative to Outcrop Motion on top of Halfspace for Nine Generic Site Profiles Considered for APR1400

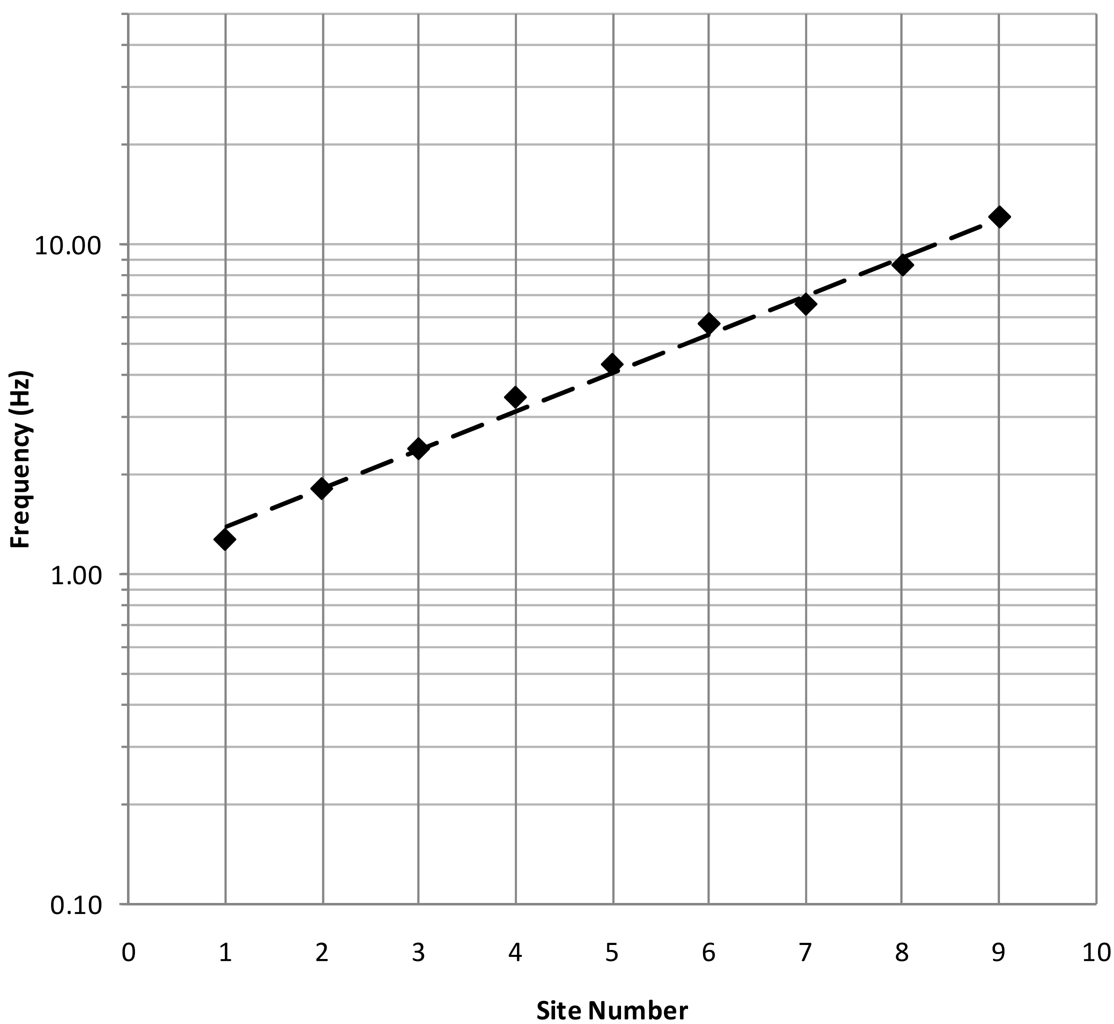

Figure 4-7. Plot of Fundamental Horizontal Site Frequencies vs. Generic Site Profile Numbers

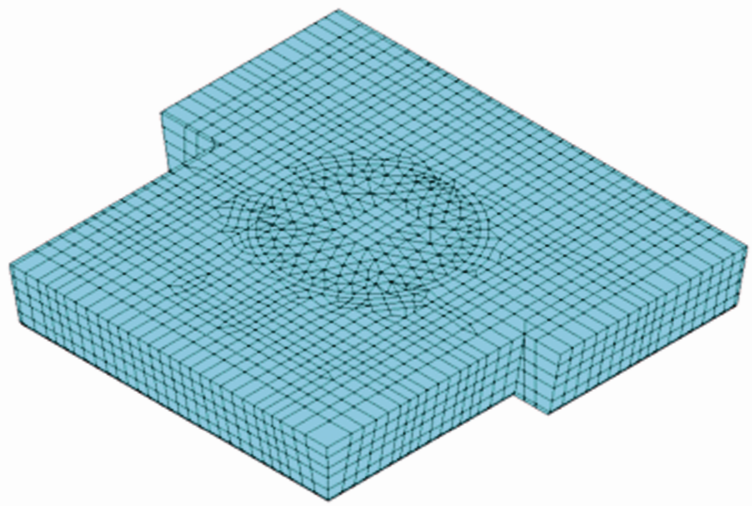

Figure 5-1. Configuration of SASSI Finite Element Model of Excavated Soil Volume of APR1400 NI Structure Foundation

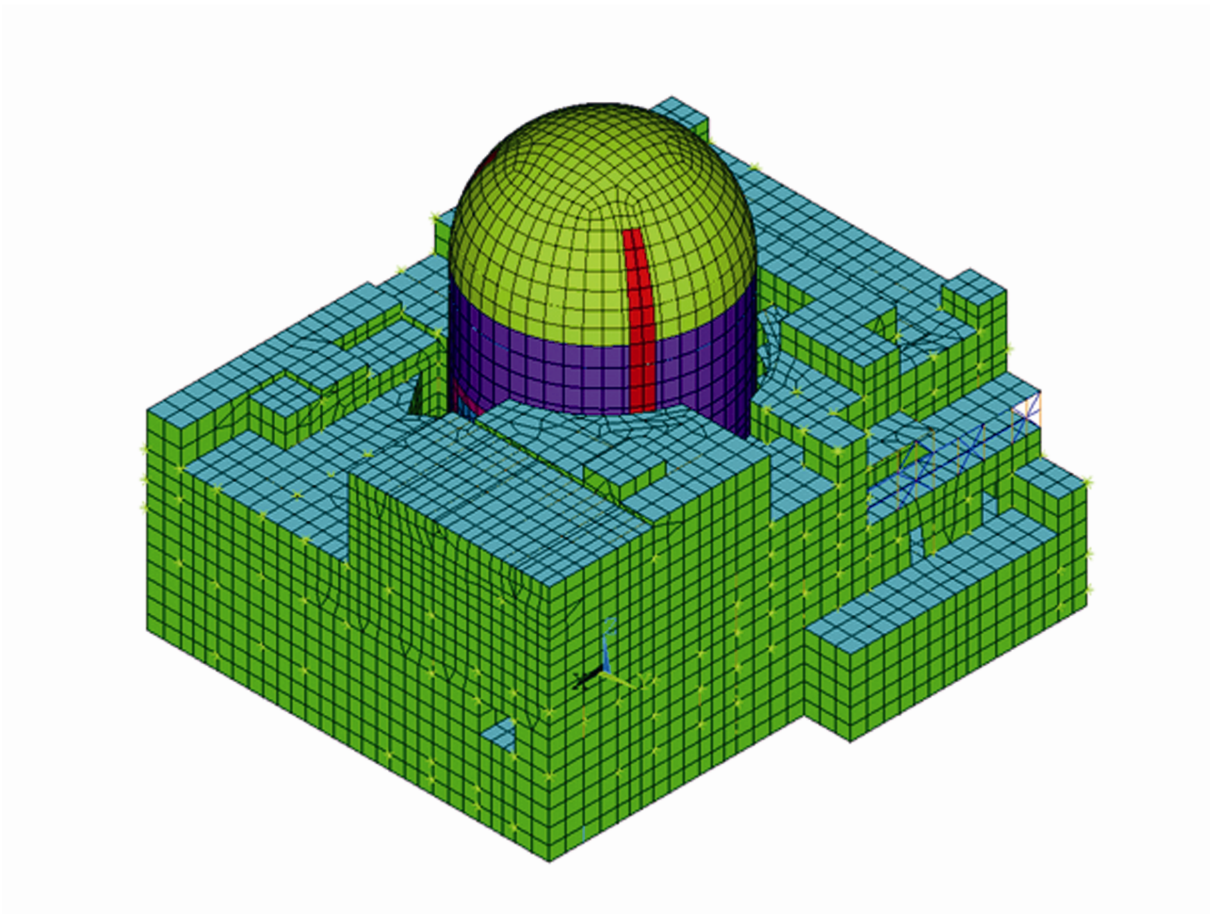

Figure 5-2. Configuration of SASSI Finite Element Model of APR1400 NI Structures

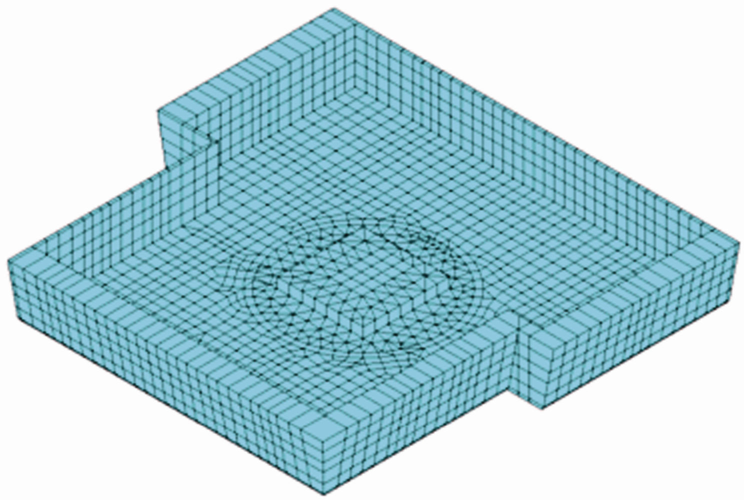

Figure 5-3. Configuration of SASSI Finite Element Model of the SFG and Lean Concrete Backfill of APR1400 NI Structures

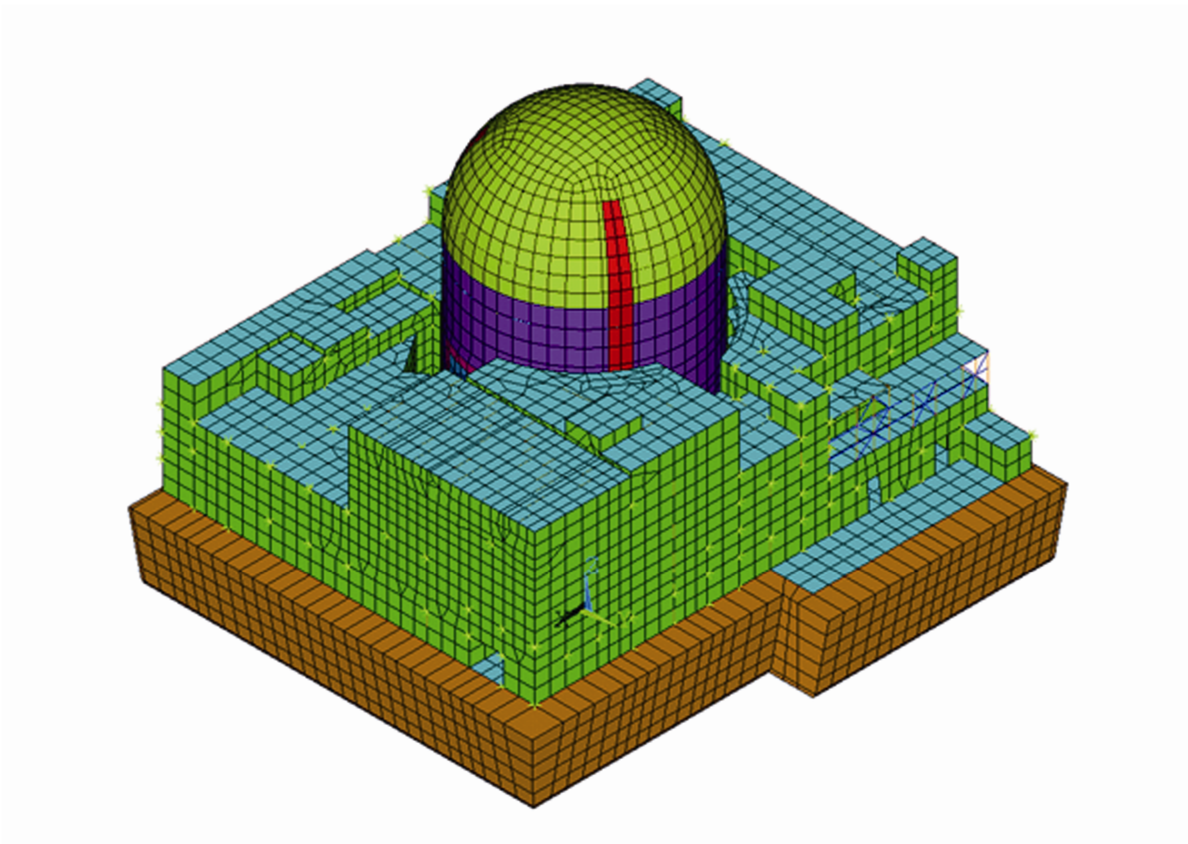

Figure 5-4. Configuration of the Complete SASSI Finite Element Model of SSI System of APR1400 NI Structures