FINITE ELEMENT SEISMIC MODELS FOR SSI ANALYSES OF THE NI BUILDINGS OF THE APR1400 STANDARD PLANT

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ABSTRACT

This technical report provides the finite element model used in soil-structure interaction analysis for the APR1400 Nuclear Island structures. The Nuclear Island structures consist of the Reactor Containment Building and Auxiliary Building and are founded on monolithic common basemat. Above the basemat, the Reactor Containment Building and Auxiliary Building are separate structures with a minimum seismic gap of 2 in. Therefore, the finite element models for each building are developed separately.

Two finite element models for each building, namely, a fine-mesh finite element model and a coarse-mesh finite element model, are developed using the ANSYS computer program.

The fine-mesh finite element model is developed with a finite element mesh that is sufficiently refined for a detailed structural analysis. The coarse-mesh finite element model is developed with larger finite element size to reduce the model's total number of degrees of freedom to a level that can be accommodated by the presently available SASSI computer program.

Model validation is made in which the dynamic properties of coarse-mesh finite element model are compared against the corresponding dynamic properties of the fine-mesh finite element model. This validation is intended to demonstrate that both models are capable of representing the natural vibration modal properties sufficiently accurately up to a high frequency cut-off of at least 50 Hz.

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List of Acronyms

3-D	Three-dimensional
AB	Auxiliary Building
AFW	Auxiliary Feed Water
ASCE	American Society of Civil Engineers
CL	Centerline
CS	Containment Structure
DOF	Degrees Of Freedom
EW	East-West
FEM	Finite Element Model
ICI	In Core Instrumentation
IRWST	In-Containment Refueling Water Storage Tank
IS	Internal Structure
ISRS	In-Structure Response Spectra
NI	Nuclear Island
NRC	U. S. Nuclear Regulatory Commission
NS	North-South
OBE	Operating Basis Earthquake
PSW	Primary Shield Wall
PZR	Pressurizer
RCB	Reactor Containment Building
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RG	Regulatory Guide
RV	Reactor Vessel
SFG	Structural Fill Granular
SG	Steam Generator
SRP	Standard Review Plan
SSE	Safe Shutdown Earthquake
SSI	Soil-Structure Interaction
SSW	Secondary Shield Wall

1.0 INTRODUCTION

The purpose of this technical report is to present the methodologies used to develop the Finite Element Seismic Models for the Nuclear Island (NI) structures. The NI finite element seismic models are developed for use in three-dimensional (3-D) seismic soil-structure interaction (SSI) analysis of the APR1400.

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 separate 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, hemispherical dome, and reinforced concrete internal structure that are supported on a reinforced concrete mat foundation.

The AB wraps around the RCB, leaving a seismic gap space 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 RCB and AB finite element models (FEMs) are developed separately and then combined (i.e., the AB structure, RCB structures, and the common basemat are combined in one coupled NI structural FEM). All finite element seismic models are developed and combined using the ANSYS computer program. The ANSYS FEM of the combined NI is converted to a SASSI 3-D FEM for seismic SSI analysis.

This technical report consists of seven (7) sections. Section 1 is an introduction that includes background information. Section 2 describes the methodology of the FEM development for the NI structures. Section 3 presents the modeling process for the RCB finite element seismic model. Section 4 describes the modeling process for the AB finite element seismic model. Section 5 describes the validation of the RCB and AB finite element seismic models. Section 6 provides the final combined FEM to be used in SSI analysis. Section 7 contains the cited references.

Appendix A contains the general arrangement drawings for the NI structures.

2.0 METHODOLOGY OF FEM DEVELOPMENT FOR NI STRUCTURES

the following considerations are made in the FEM development for the APR1400 NI structures:

- The APR1400 NI structures have a maximum embedded ratio (embedment depth/AB building height=55/171.8) of 0.320 and are considered embedded structures for the seismic SSI analysis.
- Estimates of the maximum frequencies of seismic wave propagation for the nine (9) soil profiles defined in the APR1400 are shown in Table 2-1 for soil layers that are 11 ft thick in the embedment. Among the nine (9) soil cases, five (5) have a maximum frequency above 50 Hz. A soil layer thickness of 11 ft is considered adequate and is accordingly adopted as the mesh size for soil elements and for the NI structural FEM.
- The 10 ft basemat is modeled by shell elements at the bottom surface of the basemat, rather than at the middle surface. This consideration can be justified as the SSI effects are accounted for more closely.
- The effects of vertical shear deformation in a 10-ft-thick common basemat on the seismic SSI analysis are considered insignificant.
- The effects of stiffnesses of local walls (not designed for the shear wall system) on the SSI response are considered small and are not included in the model.

The purpose of the model development is to create a 3-D FEM for SSI analysis of the APR1400 NI structures, which includes the RCB and AB founded on a common basemat. The 3-D SSI analysis is carried out using the SASSI program. The development of a complex 3-D finite element SASSI model of the NI structures consists of the following steps:

- A 3-D primitive model consisting of geometric properties of lines, areas, and volumes is created using the ANSYS program and based on data from the APR1400 drawings. The ANSYS primitive model consists of lines for columns and beams, areas for walls and slabs, and volumes for solid structural components, using key points to define key locations of physical wall-slab connection joints. In the primitive model, all material and geometrical properties are prepared.
- Based on the ANSYS primitive model, fine and coarse models are generated with specified element types, properties, and required mesh sizes.
- The ANSYS coarse model is validated by constructing an ANSYS fine model, obtaining analysis results, and comparing the results to the analysis results of the ANSYS coarse model.
- When the ANSYS AB and RCB coarse models have been verified, the primitive models are combined to create an ANSYS coarse 3-D FEM of the NI structures.
- The ANSYS coarse 3-D FEM of NI structures is converted to SASSI for a 3-D SSI analysis of NI structures.
- The SASSI 3-D FEM of NI structures is numerically optimized for efficient SSI computation.
- The SASSI 3-D FEM of NI structures is verified with its seismic response time histories obtained from the fixed-base condition against those obtained from the ANSYS coarse fixed-base 3-D FEMs of the AB and RCB. The SASSI 3-D FEM of NI structures can be verified by comparing the In-Structure Response Spectra (ISRS) at selected locations.

3.0 REACTOR CONTAINMENT BUILDING MODEL

This section describes the RCB structures and the methodology for developing the APR1400 RCB FEM.

3.1 Description of RCB Structures

The APR1400 RCB is a safety-related Seismic Category I structure that consists of three concrete substructures:

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

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

The CS and IS are separated by a 2 in gap and only connected at their basemat at El. 78'-0". Therefore, there is no interaction between the two structures except through the common basemat. The structural elements between the CS and IS are included in the SSW. The primary dimensions of the RCB are listed in Table 3-1. Figures A-1 through A-7 of Appendix A are section and plan views of the RCB.

3.1.1 Containment Structure

The CS consists of a cylindrical post-tensioned shell with 4.5 ft thick walls. The dome is hemispherical with 4 ft thick walls. The line at the intersection of the cylindrical and hemispherical shapes is called the spring line and lies 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 on the north side, and two are on the east side.
- The personnel emergency exit airlock openings (one on the north side and one on the east side) are at center El. 103'-9" and azimuth 280°.
- The personnel access airlock openings (one on the north side and one on the east side) are at center El. 159'-9" and azimuth 234°.

The CS has one equipment hatch opening. The opening is on the east side, has a 26 ft circular opening, and is at center elevation at 167'-6" and 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° 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 the CS shell structure is lined on with a 0.25 in steel liner plate, which acts compositely with the CS.

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

3.1.2 Primary Shield Wall

The IS includes the PSW and SSW. The IS is supported by a concrete basemat that extends from El. 45’-0” to El. 78’-0”. The PSW is a concrete rectangular block with an area of 61’-8” x 37’-6” that extends from El. 69’-0” to El. 130’-0”, as shown in Figure 3-2. The rectangular block supports two E-W walls with variable thicknesses that extend from the top of the rectangular block at El. 130’-0” to their top elevation at 191’-0”, as shown in Figure 3-3. The concrete rectangular block has a 24 ft diameter opening that houses the Reactor Vessel (RV) in the east side. The west side of the rectangular block 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, and the Refueling Pool is at El. 114’-0” on the east side between the PSW and SSW. The concrete block has six openings, each 6 ft in diameter, which allows the hot and cold legs to penetrate the rectangular block that connects to the RV. Inside the concrete pedestal support is a Reactor Cavity (pit) below the RV that extends from El. 69’-0” to El. 78’-0”.

3.1.3 Secondary Shield Wall

The SSW consists of a cylindrical perimeter wall with a 51 ft radius (at the centerline) that protects the primary shield structure. The SSW is 4 ft thick from top to bottom. The SSW acts as the primary supporting structure to 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 PSW and SSW at El. 78’-0” and El. 100’-0” is filled with concrete that forms a ring with a 51 ft radius that is penetrated by the rectangular block of the PSW.

The other major SSW components that are considered in this document are:

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

The IRWST is an annular cylindrical tank that is 26 ft wide and 22 ft high and that 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 supports the IS slabs above creating vertical load paths 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 that form a square that extends to El. 200’-0”. The PZR walls are 21 ft long and are directly supported by both the PSW and SSW.

3.1.4 Reactor Coolant System

The major RCS components are shown in Figure 3-4 and are as follows:

- The Reactor Vessel (RV), which is supported by four columns and by the PSW
- Two Steam Generators (SGs), which are supported horizontally by the PSW and SSW and vertically at the base by concrete pedestals at El. 112’-10”
- The four (4) Reactor Coolant Pumps (RCPs), which are supported laterally on beams spanning the PSW and SSW (at two elevations) and supported 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

3.1.5 Internal Structure

The IS foundation has two (2) cylindrical concrete volumes as follows:

The first volume shares a 10 ft deep common basemat with the AB from El. 45’-0” to El. 55’-0”. This pedestal is 167 ft diameter, 33 ft in maximum thickness (from bottom El. 45’-0”, extending up to El. 78’-0”). See Figure 3-5.

The top surface of the volume has a pit cavity 50.26 ft x 31.34 ft x10 ft deep under the RV center and is covered with a 0.25 in steel liner plate. The basemat bottom surface is not straight but has a square saddle that is 85 ft long and 10 ft deep at the center. Therefore, the approximate center of the volume is 11 ft thick.

The second volume is a pedestal stacked above the IS cylindrical basemat portion. This volume has a diameter of 102 ft and is considered part of the SSW. It extends from El. 78’-0” to El. 100’-0” and supports the cylindrical SSW, as shown in Figure 3-6.

3.2 Development of Finite Element Models for RCB Structures

3.2.1 Geometry and Coordinate System

The coordinate system that is used for the model development of the CS and SSW is primarily the cylindrical coordinate system because both structures are circular. The system is used for geometry modeling and for locating the lumped masses at the SSW circumference.

In contrast, the PSW and RCS use the rectangular Cartesian coordinate system.

The center lines of the CS and SSW are identical and are referred to as the “CL Reactor Containment Building.” The center is at the origin (0, 0, Z) in the global Cartesian coordinate system (ft units), with. X=0, Y=0, Z=vertical elevation of components based on drawings.

In general, the locations and dimensions of walls and the elevations of openings are defined in the structural drawings by the azimuth angle in degrees. The units that are used in the model are as follows:

- Length : foot
- Weight : kip
- Stress : ksf
- Mass : kip-sec^2/ft

X, Y, and Z axes based on the rectangular Cartesian coordinate system correspond to the following, as shown in Figure 3-7:

The plant N-S direction is the global Y axis with:

- Azimuth AZ. 180° for (+Y) pointing to the plant north.
- Azimuth AZ. 0° for (-Y) pointing to the south.

The East-West (EW) direction is the global X axis with;

- Azimuth AZ. 270° for (+X) pointing east.
- Azimuth AZ. 90° for (-X) pointing west

The RV centerline is offset by 1 ft to the east from the center line of the RCB centerline. The RCB centerline is at the origin of the model at (0, 0, 0). The RV centerline is at (1, 0, Z) in the Cartesian global coordinate system (i.e., X=1 ft, Y=0 ft, Z=vertical elevation of RV components). Consequently, due to the 1 ft offset, the IS is only symmetric about the X global axis (EW).

3.2.2 Material Properties

The structural material strength, stiffness, and weight density that affect the dynamic responses of the RCB are summarized in Table 3-2.

For the uncracked concrete condition, the uncracked concrete stiffness properties are represented by the concrete modulus of elasticity (E_c) as given in Table 3-2 times the uncracked concrete gross section properties.

For the cracked concrete condition, the effective stiffnesses of reduced, cracked concrete section properties are represented by the reduced concrete modulus of elasticity ($\overline{E}_c$) times the uncracked concrete gross section properties. The reduced concrete modulus ($\overline{E}_c$) values used to represent cracked concrete stiffness in the RCB seismic analysis are summarized in Table 3-3.

3.2.3 Structural Member Modeling

Structural members are modeled using finite elements as required by Subection 4.5.4 in the APR1400 design criteria (Reference 1). Shear walls and main structural walls are modeled using shell elements in ANSYS with the element centerline modeled at mid-plane. Massive concrete areas are modeled using solid “brick” elements. Large aspect ratio and abnormal geometry in element shapes are avoided. Grating floors, being non-structural, are not modeled.

3.2.4 Minimum Frequency of Seismic Wave Passage

For subgrade portions of the structure, the mesh size is controlled by the soil thickness, which is required to satisfy the minimum frequency. A cut-off frequency of 50 Hz is used for seismic wave passage through rock, and hard and moderate soil profiles. Cut-off frequencies between 20 and 40 Hz are used for soft soil profiles.

3.2.5 Modeling of Mass (Structural Mass, Live Loads, Floor Loads and Equipment Loads)

The equivalent dynamic mass applied on the detailed finite element consists of the structure self-weight in addition to all permanent equipment weight. There is no live load assigned to the RCB slabs as floor loads. The masses are developed following the required APR1400 design criteria in Chapter 4, Subection 4.7.4 (Reference 1).

In addition to the structural mass, mass equivalent to a distributed floor load of 50 psf is considered to represent miscellaneous dead weight such as minor equipment, piping and raceway, as required in Section 4.6 of the APR1400 design criteria for structural containment loading. Also, a mass equivalent to 25% of floor live load or 75% of 75 psf of snow load required by U.S. Nuclear Regulatory Commission (NRC) Standard Review Plan (SRP) 3.7.2, Part II, 3(D), in the acceptance criteria are applied on the roof. This criterion is applied to the CS dome. The mass of major equipment is distributed over specific tributary areas where applicable.

The applied loads from which masses are derived for the RCB are:

- Structure Self Weight:
  Table 3-2 shows the mass densities used to represent the self weight of the RCB. Additional mass density is added to the CS shell density to account for a 0.25 in steel liner plate that is compositely attached to the interior face of the CS cylinder and dome. To account for miscellaneous loads such as pipes, tank water and steel liner plates, an additional load of 10 psf is added to exterior walls, and 20 psf is added to all interior walls.

- Polar Crane Loads:
  The polar crane load including the main girders (bridge), polar crane ring, trolley and rail and accessories is approximately 2,500 kips. In addition, the polar crane attachment to the CS by means of steel brackets and steel ring beam weigh 500 kips. In summary, the total weight of the polar crane and its supporting system is approximately 3,000 kips. The polar crane is parked at azimuth 243°.

- Water Mass Loads:
  The IRWST water mass is approximately 5,530 kips and is included in the FEM.

- Pipe Loads:
  A 50 psf distributed dead load is applied on all RCB slabs to account for pipe loads attached to floor slabs, satisfying the U.S. NRC SRP 3.7.2, Part II, 3(D), of the acceptance criteria.

- RCS Weights:
  The self weight of the RCS supported at various elevations of the RCB is approximately 9,073 kips. This consists of various equipments and their attachments, components such as pipes, pumps,

pressurizer and steam generators.

- Roof or Snow Loads:
  The controlling live load on the dome is 75% of 75 psf of snow loads. This load is applied as distributed to the Dome (roof) of the CS according to the U.S. NRC SRP 3.7.2, Part II, 3(D), in the SRP acceptance criteria.

3.2.6 Modeling of Damping

For conservatism, Operating Basis Earthquake (OBE) damping value of 4% for reinforced concrete and 3% for pre-stressed concrete and welded or bolted steel with friction connections are taken for the uncracked concrete case.

For the cracked concrete case, Safe Shutdown Earthquake (SSE) damping values of 7% for cracked reinforced concrete and 4% for steel connections, as well as 5% for pre-stressed concrete, are used. This criterion is in compliance with U.S. NRC Regulatory Guide (RG) 1.61 (Reference 9). A low critical damping ratio of 0.5% is used for sloshing of water per the American Society of Civil Engineers (ASCE) 4-98 requirement (Reference 16).

3.2.7 Modeling of Hydrodynamic Effects for the IRWST

The hydrodynamic effect of significant mass interacting with the structure is considered for the IRWST in modeling the inertial characteristics in accordance with Subsection 4.5.4 in the APR1400 design criteria (Reference 1). Convective and impulsive horizontal masses and frequencies are calculated for modeling the hydrodynamic effects on tank walls.

- IRWST Description
  The IRWST is an enclosed annular cylindrical water tank located inside the RCB at El. 81'-0". Figure 3-8 is an elevation view of the tank, and Figure 3-9 is a plan view of the tank. The tank is made of reinforced concrete and consists of the roof slab, outer (exterior) wall, inner (interior) wall, and bottom slab, which rests on top of the RCB basemat. The inner radius of the outer wall is 71.83 ft, and the outer radius of the inner wall is 53 ft. The top elevation of the IRWST roof slab is 100'-0" and the top elevation of the bottom slab is 81'-0". The outer and inner walls, roof slab, and bottom slab are all 3 ft thick. The water at the normal operating level is at El. 93'-0". Thus, the water height (from the top of the bottom slab to the bottom of the roof slab during normal operation is 12 ft, and the freeboard (water surface to the bottom of the roof slab) is 4 ft.

- Hydrodynamic Analytical Approach
  The analytical approach used to model the horizontal hydrodynamic effect on the annular cylindrical tank is based on the formulations given by Tang et al. (Reference 13), which are based on the previous study of dynamic responses of an annular cylindrical tank under horizontal seismic motion by Aslam et al. (Reference 14). This approach is also presented by R. A. Ibrahim.

  The hydrodynamic effects on the rigid tank in the formulation in Reference 13 can be simplified to equivalent mechanical models consisting of impulsive and convective parts similar to those formulated by Housner for cylindrical and rectangular tanks. The impulsive part represents a certain portion of water that moves as a rigid body with the bottom and walls. The convective part represents an oscillating (sloshing) portion of a certain portion of water responding as if it is an oscillating mass flexibly connected to the walls. Using the formulation given in Reference 13, the hydrodynamic properties of equivalent IRWST mechanical models, such as impulsive mass for the impulsive part, and sloshing frequencies and masses for the convective part, can be calculated.

For the vertical vibration, all of the water in the tank is assumed to move vertically as a rigid body with the vertical motion of the tank base. Thus, all of the vertical water mass in the tank is uniformly distributed as lumped masses attached to structural nodes at the bottom of the tank.

- Summary of IRWST Hydrodynamic Properties
  The hydrodynamic properties for impulsive and convective parts are summarized in Table 3-4. In this table, the masses, frequencies, and axial spring stiffnesses of equivalent mechanical models are listed for the impulsive part, and the first two dominant sloshing modes for the convective parts.

The hydrodynamic effects of impulsive and convective parts of water contained in the IRWST are modeled separately by FEM using simplified mechanical models as described below.

- Impulsive IRWST Models
  In order to simulate the impulsive forces to exert forces normal to the tank walls during horizontal seismic motion, the horizontal impulsive part of water, which represents the rigid portion of water mass moving with the tank, is modeled as a rigid circular ring-lumped mass, axially rigid radial beams (trusses) system, as shown in Figure 3-10. The impulsive mass given in Table 3-4 is uniformly distributed as lumped masses connected on a rigid circular ring. Each mass has two dynamic degrees of freedom (DOFs) acting in the horizontal global X and Y directions and is equal to the impulsive mass given in Table 3-4 divided by the number of nodes on the ring.

  The rigid circular ring is made of inter-connected rigid beam with large axial and flexural properties to ensure that all impulsive masses move together as one system. The rigid ring is connected to axially flexible radial beams, which are connected to structural nodes on the FEM of the inner-tank wall. The radial beams have a large axial property and very small shear and flexural properties to simulate truss elements so the impulsive forces exert normal to the tank wall.

  For the vertical vibration, all of the water in the tank is assumed to move vertically as a rigid body with the vertical motion of the tank base. Thus, the vertical impulsive model consists of lumping all of the water mass attached to FEM structural nodes at the tank base, as shown in Figure 3-12. Each lumped mass has only one dynamic DOF in the vertical global Z direction, and is equal to the total water mass contained in the tank divided by the number of structural nodes at the tank base.

- Convective IRWST Models
  In order to simulate water loads acting normal to the tank wall, the first two dominant modes of vibration of the convective part of the water in the tank, which represent the oscillating portion of water in the tank, are modeled by two lumped mass radial beam systems, as shown in Figure 3-11. The lumped masses for the first and second modes given in Table 3-4 are placed at the center of the tank. Each lumped mass is then connected to 41 axially flexible radial beams, which are connected to structural nodes on the FEM of the inner tank wall. The water damping ratio of 0.5% for horizontal sloshing modes, as required by ASCE 4-98, “Seismic Analysis and Safety-Related Nuclear

Structures and Commentary," is used as the damping value for radial beams in the ANSYS FEM.

3.2.8 Modeling of Polar Crane

The polar crane is modeled in the FEM. The polar crane is a standard two-girder overhead crane with end trucks at the girder centerlines. The crane is supported by the CS cylindrical shell at El. 241'-0". Figure 3-13 shows the details of modeling the polar crane in ANSYS.

The polar crane system is modeled at its parked location at azimuth 243°. The trolley masses and upper platform are modeled at the bridge girders in the second quarter of span location.

The polar crane model consists of the following:

- Two main steel girders are modeled to represent the bridge beams and support the trolley. The bridge wheels have been also modeled to represent the bridge width using rigid beams at all four (4) corners.
- The trolley is not modeled. The trolley structure is rigid and spans the two (2) main girders. It is idealized at its parked location by means of two (2) rigid mass less steel cross beams spanning the main girders forming the trolley frame. The trolley mass is accounted for as lumped mass.
- The ends of the main crane girders are connected with rigid end ties (beams). These beams are tapered but only the typical section is modeled uniformly across the end tie beam length.
  Note: +X axis pointing east, at azimuth 270°.
- The crane girders and trolley are supported by two (2) steel ring beams. The inner one called the rail ring, has a radius of 71.65 ft from the CS center, while the outer radius is the same as the CS cylindrical radius, which is 77.25 ft.
- The inner ring beams are supported at 50 locations by stiff steel corbels or brackets.
- The outer steel ring beam is embedded in the concrete CS cylindrical shell and attached to all its shell elements at all the intersection nodes based on the FE mesh discretization.

3.2.9 Modeling of CS

The CS is modeled using finite elements given uniform thickness per the structural drawings. All shell elements used to model the CS represent the centerline of the structure walls (i.e., shell elements modeled at their mid-plane). ANSYS SHELL63 elements have both bending and membrane stiffness. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node: translations in the nodal X, Y, and Z directions and rotations about the nodal X, Y, and Z axes.

3.2.10 Modeling of PSW

The PSW has two (2) portions: the solid block up to El. 130'-0" and the shell shield wall above it to El. 191'-0".

- The six (6) openings of the hot and cold legs as shown in Figure 3-14, were considered. The penetration of the leg passing through the massive block is idealized, as shown in Figure 3-15, using a rectangular opening of 5 ft x 6 ft.

- The interface between shell elements and solid brick elements has been done using rigid beam elements with high axial, bending and shear stiffness to provide continuity at transitions of different element types. See Figures 3-16 and 3-17.
- At the RV column supports location, inside the cavity, the diamond shape that provides pads for the column supports is modeled as circular, offering a pad that is approximately 3.2 ft wide. The inner circle diameter (dashed) is approximately 17.6 ft. See Figure 3-18.

3.2.11 Modeling of SSW

The SSW is idealized at its centerline as shown in Figure 3-19. The dashed blue lines indicate the idealization of walls and tanks. The dashed red lines indicate the concrete foundation top surface and cavity pit simplifications.

The SSW is modeled with shell elements. At the interface with the concrete base (El. 78'-0"), there is a massive concrete volume between the PSW and SSW called a pedestal (El. 78'-0" to El. 100'-0") that is modeled with eight (8) node solid elements. The transition between the solid concrete volume and the cylindrical shell is accomplished by extending the shell elements to overlap with the solid volume below, providing bending stiffness continuity between element types (see Figure 3-20). This transition is better than using rigid beams.

- There is a multiple shell element penetration of the SSW inside the concrete basemat that provides stiffness continuity between the SSW shell elements and the solid concrete brick elements of the base. Mass duplication is avoided by assigning zero density to the penetrating shell elements.

3.2.12 Mesh Sizes for Generation of ANSYS Fine and Coarse 3-D FEM of RCB

The 3-D FE models have an adequate number of discrete mass degrees of freedom to capture the global and local translational, rocking, and torsional responses of the structures. The element size is selected so that the structural response is not significantly affected by further size refinement. In general, the fine model mesh size for the CS is 5 ft and for the IS approximately 6 ft. In contrast, the coarse mesh model element size is twice the fine mesh element sizes (i.e., 10 ft to 12 ft).

4.0 AUXILIARY BUILDING MODEL

This section describes the AB structure and methodology of developing the APR1400 AB FEM.

4.1 Description of AB Structure

The APR1400 AB is a safety-related Seismic Category I structure with an embedment of approximately 54 ft. It encloses the RCB in the center without structural connection except at the common basemat. The combined RCB and AB with a common basemat are generally referred to as the Nuclear Island (NI) structures. Three adjacent structures, the Emergency Diesel Generator Building, Turbine Generator Building and Compound Building, are separated from the AB with a typical 3 ft building gap. This building layout with adjacent buildings is shown in Figure 4-1. The primary dimensions of the AB are listed in Table 4-1.

The AB houses important facilities including the Fuel Handling Area, Spent Fuel Pool, Cask Loading Pit, Refueling Canal, Cask Decontamination Pit, Auxiliary Feed Water (AFW) Tanks, Main Control Room, Equipment Hatch Access, and others. The AB structural system consists of shear walls in the E-W and N-S directions and a total of seven (7) major floor and roof slabs. The walls and slabs are made of normal reinforced concrete. Columns and girders are also used to support floor and roof slabs. The shear walls have various sizes of door openings and corridors partial openings on floor slabs. Appendix A, Figures A-8 through A-18 show the AB elevations and floor plans.

4.2 Development of Finite Element Models for AB Structure

This section describes the development of 3-D AB FEM for SSI analysis.

4.2.1 Coordinate System

A rectangular Cartesian coordinate system is used for the ANSYS and SASSI models. The origin in a horizontal plan of this coordinate system is located at the center of the RCB. In this coordinate system, the positive X points to the plant east direction, the positive Y to the plant north direction, and the positive Z to the vertical upward direction, as shown in Figure 4-2.

4.2.2 Material Properties

The major AB structural components are reinforced concrete structures. Material properties of uncracked-concrete for the basemat, slabs, walls, and columns are listed in Table 4-2. Material properties for the horizontal cracked concrete model and vertical cracked concrete model are listed in Tables 4-3 and 4-4, respectively. Material properties of structural steel for columns and for girders are listed in Table 4-5. Critical damping ratios are taken from U.S. NRC Regulatory Guide 1.61(Reference 9).

4.2.3 Common Basemat for AB and RCB

The 10 ft thick basemat, as shown in Figure 4-3 serves as a common foundation for the AB and RCB. In the basemat, the central circular area with a radius of 83'-6" serves as the RCB foundation, while the rest of the basemat supports the AB with an embedment of 53'-6". The two buildings are separated with a minimum 2 in seismic gap above the top surface of the common basemat at El. 55'-0".

The AB and RCB common basemat is modeled separately in ANSYS by four (4)-node elastic SHELL63 elements for the AB at the bottom surface of the concrete foundation (El. 45'-0") to account more closely for SSI effects and by eight (8)-node SOLID45 elements for the RCB concrete foundation, as shown in Figure 4-4 for the coarse mesh. To provide continuation of rotational deformation at the interface of AB shell elements and RCB solid elements, a dummy massless ring of shell elements is extended from the edge to inside the RCB, beneath the solid elements as depicted in Figures 4-5 and 4-6.

The ANSYS elastic SHELL63 element has both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node, three translations, and three rotations.

To simulate the relatively rigid 10 ft basemat between the top (El. 55'-0") and bottom (El. 45'-0") surfaces of the concrete foundation, AB walls and columns are extended from El. 55'-0" to El. 45'-0" with massless rigid beam elements. A mesh size of 5 ft for the basemat is specified for the ANSYS fine model, while for the ANSYS coarse model a larger size of 12 ft is set to equal that determined from the requirement for soil mesh sizes limited to one-fifth of the wave length at the 50 Hz cut-off frequency. Figures 4-5 and 4-6 depict the AB basemat geometry of the ANSYS fine and coarse models, respectively.

4.2.4 Shear Walls, Partial Wall Openings (Doors, Corridors, and Others), Equivalent Wall Thicknesses and Equivalent Mass Densities

The AB shear wall system is a normal reinforced concrete structure with thicknesses varying from 4 ft to 1.5 ft at the top. For several special local areas, some walls with a thickness of 5 to 7 ft are used for the Spent Fuel Pool. Bearing walls and local minor walls that are not part of the shear wall system are not included in the model. However, the masses of these walls are included in the concentrated masses. Shear walls contain various sizes of openings, such as single doors, double doors, and corridors. To simplify the 3-D FEM, these openings are not modeled, but the effects of the openings on the shear stiffness of the wall panels are included by using an equivalent wall thickness with the stiffness factors obtained from a parametric study.

An additional 10 psf is included on each interior wall face to account for the miscellaneous dead loads attached to the walls. With the equivalent shear stiffness factors, equivalent thicknesses and mass densities of shear walls are calculated. Shear walls are modeled with ANSYS four (4)-node SHELL63 elements.

4.2.5 Floor Slabs, Partial Floor Openings, Major Equipment, Earthquake Live Loads, Roof Snow Loads, Other Miscellaneous Dead Loads, and Equivalent Mass Densities

The AB structural model comprises one basemat (El. 55'-0"), seven major floor and roof slabs (El. 78'-0", 100'-0", 120'-0", 137'-6", 156'-0", 174'-0", and 195'-0"), and four minor partial floor and roof slabs (El. 68'-0", 213'-0", 213'-6", 216'-9"). The basemat and its supported equipment are modeled at El. 45'-0". Floors at El. 68'-0" and 78'-0" are modeled with a small adjustment made to shift the centerlines of the floor slabs at El. 67'-0" and 77'-0", respectively, to align with the soil layer elevations in the SSI model.

Floor slabs have some partial openings, which are included in the model geometry.

Major APR1400 AB equipment loads are listed in Table 4-6, while seismic live loads, roof dead loads, roof snow loads, and other miscellaneous dead loads are given in Table 4-7.

In addition to the floor loads, the weight of floor construction steel beams used to temporarily support the concrete weight before curing is included to calculate the total equivalent mass densities for floor slabs. Floor slabs are modeled with ANSYS four (4)-node SHELL63 elements.

4.2.6 Modeling for Out-of-Plane Vertical Flexibility of Floor Slabs

To develop a coarse ANSYS 3-D AB FEM, a step is needed to verify the accuracy of the coarse model by using a fine model with a smaller mesh size. This is particularly important for the out-of-plane vertical flexibility of floor slabs. A study was conducted to identify any property adjustments that are needed in floor panels in the coarse model to obtain the same flexibility as those for the fine model.

In the study, the ANSYS fine and coarse 3-D AB FEMs were cut at the upper and lower floors for a floor in the study. Fixed boundary conditions were specified at all nodes of the cut planes. ANSYS modal analyses of selected floor slabs were performed for both separated models. Comparisons of fundamental frequencies for these floor slabs were made panel by panel. If the fundamental frequency of the fine isolated model was lower than 50 Hz and was 5% greater than that of the coarse isolated model, the modulus of elasticity of the panel in the coarse model was adjusted by:

$$E_m = E\,(F_f/F_c)^2$$

Where E_m= Adjusted modulus of elasticity of concrete for the panel of the coarse model under study
E = Modulus of elasticity of concrete for the panel under study
F_f = Fundamental out-of-plane vertical frequency of the panel in the fine model
F_c = Fundamental out-of-plane vertical frequency of the panel in the coarse model before adjustment

The results of the study are summarized in Table 4-8.

4.2.7 Modeling for Columns and Girders

Columns and girders in the AB are modeled with beam elements. Most columns are embedded in walls with a few exceptions. Those columns are added to the model with its center line modeled at the center line location of the wall which is modeled by shell elements.

With the concrete section already presented in the shell element the for floor slab, the girder is modeled at the centerline of the shell element.

4.2.8 Concentrated Masses for Minor Structural Components Not Modeled

Minor structural components such as local bearing walls, small local slabs, and parapets are not modeled, but these masses are lumped at supporting shear walls.

4.2.9 Modeling of Hydrodynamic Loads for AFW and FHA Tanks

There are six (6) AFW tanks on the ground floor at El. 100’-0”, one Spent Fuel Pool at El. 114’-0”, one Cask Loading Pit at El. 111’-0”, and one Refuel Canal at El. 114’-6”. The hydrodynamic effects from these water tanks are included with horizontal hydrodynamic mass and support stiffness to simulate horizontal sloshing (convective) masses of water attached with flexible springs to the upper portion of the tank wall. Horizontal impulsive hydrodynamic mass is calculated as lumped masses attached rigidly to the lower portion of the tank wall. The hydrodynamic effects on two horizontal (E-W & N-S) directions are considered separately. In the vertical direction, the total water mass is lumped at the bottom slab of the tank.

4.2.10 Mesh Sizes for Generation of ANSYS Fine and Coarse 3-D AB FEM

Because the thickness of shear walls generally varies from 3 to 4 ft, the mesh size for an ANSYS fine 3-D FEM also should not be less than 4 ft. With other considerations for structural modeling, a mesh size of 5 ft is selected for the ANSYS fine 3-D FEM. The 5 ft mesh fine model, by estimation, exceeds the model size limits for the ACS SASSI program. The fine model can, however, be considered as a base model for verification of a coarse model. The coarse model can be used for seismic SSI analysis to satisfy (1) the 12 ft mesh size requirement for a 50 Hz cut-off frequency and (2) the model size requirement of the ACS SASSI program. Accordingly, a mesh size of 12 ft is determined to be adequate for use in the ANSYS coarse 3-D AB FEM.

4.2.11 Geometry Plots of ANSYS Fine and Coarse 3-D AB FEM

The ANSYS fine and coarse 3-D AB FEMs were created. Table 4-9 summarizes the two FEMs.

Figure 4-7 depicts the ANSYS fine 3-D AB FEM, while Figure 4-8 depicts ANSYS coarse 3-D AB FEM. Figure 4-9 shows a view looking north into the interior modeling with a vertical cut at column line AG (to avoid blocking by the wall at column line AF). Figure 4-10 is another view looking west into the interior modeling, with a vertical cut at column line 19.

4.2.12 Minimum Frequency of Seismic Wave Passage

For subgrade portions of the structure, the mesh size is controlled by the soil thickness, which is required to satisfy the minimum frequency. A cut-off frequency of 50 Hz is used for seismic wave passage through rock and hard and moderate soil profiles. Cut-off frequencies between 20 and 40 Hz are used for soft soil profiles.

5.0 VERIFICATION OF SEISMIC MODEL

5.1 Verification of RCB Model

To verify the RCB seismic analysis model to be used in the SSI analysis, the following comparisons with the fine 3-D FEM are performed under the fixed-base condition.

- Modal properties
- Static displacements of 1g
- ISRS using time history analysis

5.1.1 Comparison of Modal Analysis Results

The modal solution is required because the structure's mode shapes and frequencies must be available for comparison between the fine mesh and coarse mesh models. Modal analysis is used to determine the natural frequencies and mode shapes of a structure. The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions and are required to perform a transient time history analysis.

Consequently, to verify dynamic properties of the developed ANSYS models, modal analyses of the ANSYS fixed-base coarse and fine mesh models are performed.

Figures 5-1 through 5-3 compare the major natural frequencies in all three directions (X, Y and Z) and cumulative modal participation mass ratios. Figures 5-4 through 5-8 present the mode shapes and Tables 5-1 and 5-2 show the fundamental major frequencies and their mass participation factors.

5.1.2 Comparisons of Static Displacements

In this subsection, unit acceleration (1g) is applied in each of the three directions to the coarse and fine FEMs in order to validate the stiffness of the RCB coarse FEM. Several nodes are selected along the height of the RCB and the displacements due to unit acceleration are compared for both models.

Different nodes are selected at the CS, PSW, and SSW structures. The approximate locations of such nodes in plan view are shown in Figures 5-9 through 5-11. The displacements are shown in Figures 5-12 through 5-20.

5.1.3 Comparisons of ISRS

The dynamic response for the coarse ANSYS fixed-base FEM and the corresponding response in the ANSYS fine model are compared via uni-directional ISRS at different locations. The selected nodes and their coordinates are shown in Subsection 5.1.2.

A 5% spectral damping value is used for the comparison. The frequency interval used for ISRS development follows SRP Section 3.7.2. Figures 5-21 through 5-29 show ISRS plots of the ANSYS coarse model versus ANSYS fine model.

Once the RCB seismic analysis model has been verified, the ANSYS coarse FEM is converted to SASSI and the validation is repeated at this level to ensure that the conversion is done properly.

5.1.4 SASSI Model Validation

The dynamic response for the coarse ANSYS fixed-base FEM and the corresponding response in the SASSI model are compared via ISRS at different locations. The selected nodes and their coordinates are shown in Subsection 5.1.2.

A 5% spectral damping value is used for the comparison. The frequency interval used for ISRS development follows SRP Section 3.7.2. Figures 5-30 through 5-38 show ISRS plots of the ANSYS coarse FEM versus SASSI FEM.

5.2 Verification of AB Model

To verify the AB seismic analysis model, modal properties, static displacements and ISRS are compared.

5.2.1 Comparison of Modal Analysis Results

Modal analyses are performed for the two ANSYS models to obtain a total of 2,500 modes by using the ANSYS Lanczos iteration option.

Tables 5-3 through 5-5 are comparisons of the major modal frequencies and masses for the dominant modes computed from the fine and coarse ANSYS models for the X, Y, and Z directions, respectively. The frequencies are sorted by the descending order of the modal masses.

Tables 5-3 and 5-4 show a reasonable agreement between the fine and coarse models for the two horizontal directions. The comparison for the vertical direction in Table 5-5 shows a larger difference in frequency for relatively close values of modal mass. The difference is reasonably expected because of differences in the modeling of floor slabs between the two models. The coarse model used in this verification lacked the vertical out-of-plane flexibility adjustment.

Figures 5-39 to 5-41 are comparisons of cumulative mass ratios between the fine and coarse models for X, Y, and Z directions, respectively. The three cumulative mass ratios of the two models compare well.

The comparisons of modal properties also indicate that AB horizontal dominant frequencies are 5.15 Hz and 5.34 Hz in the EW and NS directions, respectively. The dominant vertical frequency is 14.5 Hz.

The computation of these modal masses does not include a rigid body mode. Therefore, a large percentage of total mass is not accounted for in the cumulative masses, in the two horizontal directions, and in the vertical direction.

5.2.2 Comparisons of Static Displacements

Static analyses for 1g gravity loads are performed by applying a 1g-acceleration in each of the three directions separately to both ANSYS fine fixed-base and ANSYS coarse models using the ANSYS program.

Static displacements obtained from both ANSYS fine and coarse models at selected locations of four building corners are plotted in Figures 5-42 through 5-45. Comparisons of the static displacement results between the two ANSYS models show good agreement.

5.2.3 Comparisons of ISRS between ANSYS Fine, ANSYS Coarse, and SASSI Fixed-base Models

Two model verifications are presented in this subsection. The first is verification of the ANSYS coarse fixed-base model against the ANSYS fine fixed-base model and the second is verification of the SASSI fixed-base model against the ANSYS coarse fixed-base model.

ISRS of 4% damping for selected locations of the three fixed-base AB models are shown in Figures 5-46 through 5-65.

The ISRS figures indicate that the ANSYS coarse fixed-base model compares well with the ANSYS fine fixed-base model. The SASSI model also compares well with the ANSYS coarse fixed-base model.

6.0 COMBINED NI SASSI MODEL

The combined NI SASSI model for the APR1400 SSI analysis consists of the RCB and AB. These two buildings are founded on a common foundation basemat. Above the basemat, the two buildings are separate and to not have structural connections. In the plant layout, the AB is separated by 3 ft gaps from the Emergency Diesel Generator Building, the Turbine Generator Building, and the Compound Building.

6.1 Modeling of Structural Components of Combined NI

Models of RCB and AB structural components are first created in ANSYS and then converted to SASSI. A total of 32,778 nodes are created (23,524 structural nodes and 9,254 soil interaction nodes), and a total of 59,030 elements are generated (including 35,113 solid elements, 4,037 beam elements, 17,974 shell elements, and 1,906 spring elements). A total of 1,452 concentrated masses are included in the model.

At the junction of shell and solid elements, massless shell elements are used to extend shell elements into solid elements for a finite distance to make the shell rotational deformation at the junction continuous with solid elements. Figure 6-1 shows the structural model of the SASSI 3-D FEM for the combined NI structures.

6.2 Common Foundation Basemat

The common foundation basemat is a 10 ft thick slab at an embedment of 53.5 ft at its bottom surface. The basemat is modeled by shell elements at its bottom surface (El. 45’-0”). With rigid properties and massless densities, structural walls and columns are extended vertically from the top surface (El. 55’-0”) of the basemat to connect to the shell elements at the bottom surface.

6.3 Soil Excavation

A soil excavation model is created with the dimensions of the AB plus extensions in two horizontal directions as well as vertically downward for soil and lean concrete backfill. A total of 9254 interaction nodes are created with the Flexible Volume Method for this model. A mesh size of 12 ft is used for an average cut-off frequency of 50 Hz among the nine (9) soil profiles for the upper 98.5 ft of soil layers. The SASSI 3-D FEM of the excavated soil volume for the combined NI structure foundation is shown in Figure 6-2.

6.4 Bottom Lean Concrete and Side Soil Backfilled with SFG

An extra 3 ft deep excavation beneath the bottom concrete surface of the basemat is used for the lean concrete backfill. An extra side excavation varies from 12 ft wide at the bottom to 24 ft wide at the top of the soil and a 3 ft wide backfill between adjacent buildings. The extra side soil excavations are backfilled with Structural Fill Granular (SFG). The SASSI 3-D FEM of the SFG and lean concrete backfill for combined NI structures is shown in Figure 6-3.

6.5 Connections between Structural Concrete and Soil

The SASSI model has two sets of nodes at the soil-structure interface boundary. One set consists of structural concrete nodes for external walls and basemat, and the other set consists of soil interaction nodes for soil excavation and soil backfill. The two sets of nodes are coincident nodes at the same locations, and are connected by a set of rigid spring elements. With this rigid spring connection, the concrete foundation is connected to the free-field soil. The SASSI 3-D FEM of the combined NI structures with soil backfill solid elements is shown in Figure 6-4.

7.0 REFERENCES

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Table 2-1. Maximum Frequency of Seismic Wave Propagation

Soil Case	Vs (ft/sec) Averaged from a Depth of 30 m	Soil Layer Thickness (ft)	Max Frequency (Hz) of Seismic Wave Propagation=Vs/(5H)
1	1191	11	21.7
2	995	11	18.1
3	2188	11	39.8
4	1866	11	33.9
5	4257	11	77.4
6	3239	11	58.9
7	2801	11	50.9
8	6528	11	118.7
9	4796	11	87.2

Table 3-1. Summary of the Main Dimensions of RCB

Item	Dimensions (ft)
Nominal ground elevation	100.00
Nominal basement bottom elevation	45.00
Foundation thickness under CS and IS	11.00 / 33.00
Top elevation of CS dome center line	331.38
Center line radius of CS	77.25
Outer radius of IS foundation at El.78’	83.50
Wall thickness of CS cylinder	4.50
Wall thickness of CS dome	4.00
CS Buttress wall thickness	7.50
IS - Primary Shield Wall thickness	4.00 / 12.17
IS - Secondary Shield Wall thickness	4.00

Table 3-2. Material Properties for Concrete and Steel

Structural Component	Concrete Compressive Strength or Steel Yield Limit (psi)	Unit Weight (kcf)	Young's Modulus (10^5 ksf)	Poisson's Ratio	Damping	Damping
					OBE	SSE
CS	6,000	0.15	6.36	0.17	3%	5%
PSW & SSW	6,000	0.15	6.36	0.17	4%	7%
Base /Pedestal	5,000	0.15	5.80	0.17	4%	7%
Steel (1)	A588,Grade A (AISC),fy=50ksi	0.49	41.76	0.30	3%	4%

(1) Steel components include steel beams/girders made of structural shapes and steel plates

Table 3-3. Effective Cracked-Concrete Modulus of Elasticity

Member Type	Cracked Concrete Modulus of Elasticity ($\overline{E}_c$)	
	Horizontal Model	Vertical Model
Prestressed Concrete Containment Structure	0.5 E_c	E_c
Reinforced Concrete Columns and Walls	0.5 E_c	E_c
Reinforced Concrete Beams and Slabs	0.5 E_c	0.5 E_c
Reinforced Concrete Basemat	0.5 E_c	0.5 E_c

Table 3-4. Hydrodynamic Properties for Equivalent Mechanic Models In-containment Refueling Water Storage Tank

Hydrodynamic Component	Mode n	Kn (1) (lb/ft)	Mn (2) ($lb\text{-}sec^2/ft$)	Wn (3) (lb)	ωn (4) (rad/sec)	fn (5) (Hz)	hn (6) (ft)
Impulsive	rigid	rigid	5.769E+04	1.858E+06	very high	very high	5.2
Convective (Sloshing)	1	8,569	8.664E+04	2.790E+06	0.31	0.050	6.0
	2	144,500	2.647E+04	8.523E+05	2.34	0.372	7.5

Notes:
(1) Kn = Axial spring stiffness for mode n
(2) Mn = Hydrodynamic mass for mode n
(3) Wn = Hydrodynamic weight for mode n
(4) ωn = Sloshing frequency in radian/second for mode n
(5) fn = Sloshing frequency in Hertz (Hz) or cycle/second (cps) for mode n
(6) hn = Height of impulsive or sloshing mass (Mn) from the bottom of the tank at El. 81’-0” for mode n
(7) n = Mode number

Table 4-1. Main Dimensions of AB Structure

Security-Related Information – Withheld Under 10 CFR 2.390

Table 4-2. Material Properties of Uncracked-Concrete

Structural component	Unit Weight (pcf)	Compressive Strength (psi)	Modulus of Elasticity (ksf)	Poisson's Ratio	Critical Damping Ratio, SSE (%)	Critical Damping Ratio, OBE (%)
Basemat	150	5000	580,393	0.17	-	4.0
Floor Slabs	150	5000	580,393	0.17	-	4.0
Walls	150	5000	580,393	0.17	-	4.0
Columns	150	5000	580,393	0.17	-	4.0

Table 4-3. Material Properties of Horizontal Cracked-Concrete Model

Structural Component	Unit Weight (pcf)	Compressive Strength (psi)	Modulus of Elasticity (ksf)	Poisson's Ratio	Critical Damping Ratio, SSE (%)	Critical Damping Ratio, OBE (%)
Basemat	150	5000	290,197	0.17	7.0	-
Floor Slabs	150	5000	290,197	0.17	7.0	-
Walls	150	5000	290,197	0.17	7.0	-
Columns	150	5000	290,197	0.17	7.0	-

Table 4-4. Material Properties of Vertical Cracked-Concrete Model

Structural Component	Unit Weight (pcf)	Compressive Strength (psi)	Modulus of Elasticity (ksf)	Poisson's Ratio	Critical Damping Ratio, SSE (%)	Critical Damping Ratio, OBE (%)
Basemat	150	5000	290,197	0.17	7.0	-
Floor Slabs	150	5000	290,197	0.17	7.0	-
Walls	150	5000	580,393	0.17	-	4.0
Columns	150	5000	580,393	0.17	-	4.0

Table 4-5. Material Properties of Structural Steel

Material	Unit Weight (pcf)	Yield Strength (ksi)	Modulus of Elasticity (ksf)	Poisson's Ratio	Critical Damping Ratio, SSE (%)	Critical Damping Ratio, OBE (%)
Steel Column ASTM A572	490	50	4,176,000	0.30	4.0	3.0
Steel Girder ASTM A36	490	36	4,176,000	0.30	4.0	3.0
Steel Angles ASTM A36	490	36	4,176,000	0.30	4.0	3.0

Table 4-6. Major Equipment Loads

Equipment Designation	Equipment No.	Location by Column Lines	Floor Elevation (ft)	Weight (kips)
CS Heat Exchangers	M2102, M2103	AA-AB-13-15, AJ-AK-13-15	55’-0”	73.6
Seismic Category I Fire Water Tanks	M2104, M2105	AE-AF-12-13, AF-AG-12-13	55’-0”	234.5
SC Heat Exchangers	M2126, M2127	AA-AB-23-25, AJ-AK-23-25	55’-0”	87.4
Equipment Drain Tank	M2138	AG-AH-25-26	55’-0”	115.0
Diesel Fuel Oil Storage Tanks	M2233, M2234	/A-AA-13-15, /K-AK-13-15	68’-0”	1065.0
Boric Acid Concentrator	M2228	AF-AG-25-26	78’-0”	61.0
Class 1E Emergency Diesel Generator	M2302, M2303	AB-AC-13-14, AI-AJ-13-14	100’-0”	400.1
SG Blowdown Flash Tank	M2401	AB-AC-21-22	120’-0”	192.0
AB Controlled Area I Exhaust ACUs	H2405	AB-AC-24-26	120’-0”	73.3
AB Controlled Area II Exhaust ACUs	H2406	AG-AH-25-26	120’-0”	73.3
Spent Fuel Handling Machine	-	AF-AI-23-25	156’-0”	53.3
AB Controlled Area I Normal Exhaust ACUs	H2615, H26166	AA-AB-21-22, AA-AB-24-25	156’-0”	73.3
CCW Surge Tanks	M2701, M2702	AA-AB-13-14, AJ-AK-13-14	174’-0”	86.0
Fuel Handling Area Overhead Crane	M2801	AC-AD-15-16	195’-0”	276.9
AB Controlled Area II Normal Exhaust ACUs	H2808, H2809	AJ-AK-20-22, AG-AI-22-23	195’-0”	73.3

Table 4-7. Seismic Live Load, Roof Dead Loads, Roof Snow Loads, and Other Miscellaneous Dead Loads

Floor Loads	Value (psf)
Miscellaneous Dead Load (Minor equipment, piping, raceways, NRC SRP 3.7.2)	50.00
Seismic Live Load (25% of Floor Design Load 200 psf, NRC SRP 3.7.2)	50.00
Roof Snow Load (75% of roof design snow load 75 psf, NRC SRP 3.7.2)	56.25
Roofing Material Dead Load	50.00
Raised Floor (at El. 157’-9”) for Floor El. 156’-0” only	20.00

Table 4-8. Out-of-Plane Vertical Floor Flexibility Adjustment Factors for the Coarse Model

Panel Elevation (ft)	Panel Location	Fine Model Frequency (Hz)	Coarse Model Frequency (Hz)	Percent Difference (Coarse/ Fine-1)	Em Adjustment Factor $(Ff/Fc)^2$
100	15-19-AA-AB	32.3	30.4	-5.9%	1.13
100	15-19-AJ-AK	32.3	30.4	-5.9%	1.13
100	17-19-AB-AC	32.3	30.4	-5.9%	1.13
100	17-19-AI-AJ	32.3	30.4	-5.9%	1.13
120	AB-AC-24-25	20.7	19.6	-5.42%	1.12
120	AB-AC-25-26	20.7	19.6	-5.42%	1.12
120	AH-AI-22-23	33.3	31.1	-6.58%	1.15
120	AI-AJ-24-25	25.4	23.8	-6.29%	1.14
120	AI-AJ-25-26	25.4	23.8	-6.29%	1.14
120	/-AA-12-13	32.2	30.1	-6.37%	1.14
120	AK-/-12-13	32.2	30.1	-6.37%	1.14
174	17-18-AA-AB	39.9	37.7	-5.51%	1.12
174	17-18-AJ-AK	39.9	37.8	-5.26%	1.11

Table 4-9. Summary of ANSYS Fine and Coarse 3-D FEMs of AB

Element Type	ANSYS Fine 3-D FEM	ANSYS Coarse 3-D FEM
Total Number of Nodes	59,567	11,682
Number of (4-Node Elastic Shell) SHELL63 Elements	64,727	14,075
Number of (2-Node 3-D Elastic Beam) Beam4 Elements	363	298
Number of (2-Node 3-D Elastic Tapered Beam) Beam44 Elements	1,561	1,561
Number of (Structural Mass) MASS21 Elements	4,040	1,811
Total Number of Elements	70,691	17,745

Table 5-1. Containment Structure, Major Modes Comparison Fine vs Coarse Mesh Models

Selected Major CS Modes	Natural Frequency (Hz)	Natural Frequency (Hz)	Mass Ratio	Mass Ratio	Direction
	FINE	COARSE	FINE	COARSE	
1	3.47	3.49	18%	18%	X (EW)
2	3.56	3.58	16%	16%	Y (NS)
3	10.52	10.59	18%	19%	Z (Vertical)
4	10.53	10.63	6%	7%	Z (Vertical)
5	19.38	19.69	2%	1%	Drumming

Table 5-2. Internal Structure, Major Modes Comparison Fine vs Coarse Mesh Models

Selected Major IS Modes	Natural Frequency (Hz)	Natural Frequency (Hz)	Mass Ratio	Mass Ratio	Direction
	FINE	COARSE	FINE	COARSE	
1	6.09	6.27	7%	8%	Y (NS)
2	9.45	9.71	4%	7%	X (EW)
3	8.55	8.60	2%	2%	Y (NS)
4	9.65	9.91	7%	5%	X (EW)
5	23.22	23.39	13%	10%	Z (Vertical)

Table 5-3. AB, Comparisons of Major Modal Frequencies in X-Direction

ANSYS Coarse Model - X Direction				ANSYS Fine Model - X Direction			
Mode	Frequency (Hz)	Modal Mass (k-s^2/ft)	Ratio of Modal Mass/Total Mass	Mode	Frequency (Hz)	Modal Mass (k-s^2/ft)	Ratio of Modal Mass/Total Mass
75	5.1615	4380.18	1.85E-01	83	5.1422	4329.44	1.82E-01
81	5.7866	3298.40	1.39E-01	84	5.3331	2618.86	1.10E-01
76	5.3540	2536.01	1.07E-01	86	5.8235	2327.47	9.81E-02
101	10.4132	852.88	3.59E-02	85	5.6118	1042.00	4.39E-02
83	6.0871	794.33	3.35E-02	108	10.3591	1024.45	4.32E-02
95	9.0481	664.07	2.80E-02	90	6.0532	821.32	3.46E-02
102	10.5368	472.42	1.99E-02	101	9.0229	605.14	2.55E-02
82	5.9465	318.15	1.34E-02	109	10.4470	217.00	9.15E-03
96	9.3992	247.97	1.05E-02	104	9.3449	214.77	9.05E-03
86	7.3622	159.92	6.74E-03	94	7.3418	142.62	6.01E-03
262	17.3913	119.93	5.05E-03	135	12.1773	140.46	5.92E-03
132	12.2365	84.78	3.57E-03	114	10.5961	136.57	5.76E-03
128	12.0956	67.18	2.83E-03	88	5.9280	122.94	5.18E-03
265	17.5444	65.96	2.78E-03	208	15.1332	101.00	4.26E-03
146	12.8488	62.82	2.65E-03	138	12.3280	88.98	3.75E-03
114	11.3754	57.10	2.41E-03	179	13.8898	78.31	3.30E-03
98	10.1057	54.78	2.31E-03	277	17.6932	74.51	3.14E-03
136	12.3930	53.92	2.27E-03	137	12.2951	74.29	3.13E-03
100	10.2244	53.56	2.26E-03	265	17.3568	71.90	3.03E-03
197	15.1207	52.09	2.20E-03	89	5.9493	71.05	2.99E-03

Table 5-4. AB, Comparisons of Major Modal Frequencies in Y-Direction

ANSYS Coarse Model - Y Direction				ANSYS Fine Model - Y Direction			
Mode	Frequency (Hz)	Modal Mass ($k\text{-}s^2/ft$)	Ratio of Modal Mass/ Total Mass	Mode	Frequency (Hz)	Modal Mass ($k\text{-}s^2/ft$)	Ratio of Modal Mass/ Total Mass
76	5.3540	8908.01	3.75E-01	84	5.3331	8868.26	3.74E-01
75	5.1615	2922.03	1.23E-01	83	5.1422	2926.52	1.23E-01
108	11.2251	680.65	2.87E-02	119	11.1741	568.77	2.40E-02
101	10.4132	597.83	2.52E-02	108	10.3591	532.98	2.25E-02
95	9.0481	334.43	1.41E-02	99	8.8976	288.01	1.21E-02
118	11.6001	301.21	1.27E-02	86	5.8235	268.15	1.13E-02
81	5.7866	273.55	1.15E-02	104	9.3449	239.43	1.01E-02
96	9.3992	217.15	9.15E-03	125	11.5958	200.70	8.46E-03
94	8.9176	130.28	5.49E-03	109	10.4470	193.91	8.17E-03
88	7.8877	123.11	5.19E-03	124	11.5196	180.74	7.62E-03
102	10.5368	109.24	4.60E-03	101	9.0229	155.87	6.57E-03
82	5.9465	93.72	3.95E-03	121	11.2394	153.33	6.46E-03
132	12.2365	80.29	3.38E-03	85	5.6118	152.39	6.42E-03
121	11.7667	74.13	3.12E-03	137	12.2951	99.98	4.21E-03
325	19.0354	63.28	2.67E-03	96	7.8568	98.33	4.14E-03
137	12.4201	62.80	2.65E-03	123	11.4613	81.89	3.45E-03
112	11.3204	59.27	2.50E-03	326	19.0270	79.66	3.36E-03
221	16.2480	56.61	2.39E-03	138	12.3280	63.86	2.69E-03
79	5.6955	48.11	2.03E-03	95	7.7242	59.47	2.51E-03
87	7.7353	47.28	1.99E-03	454	22.0540	50.72	2.14E-03

Table 5-5. AB, Comparisons of Major Modal Frequencies in Z-Direction

ANSYS Coarse Model - Z Direction				ANSYS Fine Model - Z Direction			
Mode	Frequency (Hz)	Modal Mass (k-s^2/ft)	Ratio of Modal Mass/ Total Mass	Mode	Frequency (Hz)	Modal Mass (k-s^2/ft)	Ratio of Modal Mass/ Total Mass
171	14.5161	1002.32	4.22E-02	195	14.5999	1879.21	7.92E-02
140	12.6490	909.49	3.83E-02	124	11.5196	1565.47	6.60E-02
160	13.8459	744.37	3.14E-02	179	13.8898	895.30	3.77E-02
98	10.1057	674.52	2.84E-02	187	14.3157	574.46	2.42E-02
118	11.6001	626.86	2.64E-02	106	10.0230	545.46	2.30E-02
189	14.8251	613.38	2.59E-02	151	12.6794	496.42	2.09E-02
115	11.4160	588.05	2.48E-02	135	12.1773	482.49	2.03E-02
146	12.8488	549.38	2.32E-02	217	15.4950	466.21	1.96E-02
116	11.5104	391.75	1.65E-02	212	15.2913	410.10	1.73E-02
128	12.0956	385.22	1.62E-02	123	11.4613	318.45	1.34E-02
156	13.6659	372.74	1.57E-02	154	12.9322	311.98	1.31E-02
172	14.5338	334.65	1.41E-02	133	12.0369	290.64	1.22E-02
193	15.0402	267.94	1.13E-02	149	12.5765	281.79	1.19E-02
213	15.7221	249.18	1.05E-02	152	12.8446	264.70	1.12E-02
191	14.9820	247.46	1.04E-02	137	12.2951	213.40	8.99E-03
165	14.0172	205.62	8.67E-03	173	13.4896	158.76	6.69E-03
203	15.2950	200.69	8.46E-03	243	16.7113	136.96	5.77E-03
161	13.8857	188.54	7.95E-03	119	11.1741	136.53	5.75E-03
208	15.4281	182.84	7.71E-03	176	13.6724	135.62	5.72E-03
124	11.9398	174.28	7.34E-03	178	13.7701	134.57	5.67E-03