*Transactions*, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division V

# STRUCTURE-SOIL-STRUCTURE INTERACTION EFFECTS FOR TWO HEAVY NPP BUILDINGS WITH LARGE-SIZE EMBEDDED FOUNDATIONS

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## ABSTRACT

The US-APWR standard plant buildings consist of the Seismic Category I Reactor Building Complex (RBC) and the Seismic Category II Turbine Building (TB). The horizontal clearance between foundations of the two buildings is about 20 ft. Such a close foundation distance and comparable size and stiffness of the foundations necessitate investigation of the effect of the presence of the TB on response of the RBC to earthquake excitations through dynamic Structure-Soil-Structure Interaction (SSSI). The RBC foundation is embedded at depth of 42 feet. The embedment depth for TB foundation is about 27 feet. An integrated model of the RBC and the TB that considers foundation embedment therefore is developed and analyzed using ACS SASSI program. Resulting structural responses of the RBC to the three component earthquake excitation are compared to the responses obtained from the Soil-Structure Interaction (SSI) analysis of the standalone RBC embedded model to identify the SSSI effects. This paper presents the typical comparison results. It is concluded from the comparison that the SSSI effects of the TB on the RBC, in terms of In Structure Response Spectra (ISRS) at characteristic locations, are insignificant.

## INTRODUCTION

This paper investigates the structure-soil-structure interaction effects of US-APWR standard plant building structures. The US-APWR standard plant buildings consist of the Seismic Category I Reactor Building Complex (RBC) and the Seismic Category II Turbine Building (TB). The RBC includes the Reactor Building (RB), the two Power Source Buildings (PSB's), the Prestressed Concrete Containment Vessel (PCCV), the Containment Internal Structure (CIS), the Essential Service Water Pipe Chase (ESWPC), and the Auxiliary Building (AB). The RBC is supported on a reinforced concrete common basemat and the RB, the PSB's, ESWPC and AB are integrated reinforced concrete structures, but the PCCV and CIS are freestanding independent structures. The TB, including the electrical room, consists of steel framed superstructures supported on the top slab of the reinforced concrete substructures with a supporting common basemat. As shown in Figure 1, the RBC basemat has an irregular shape consisting of a rectangular part with footprint dimension of 340 feet by 310 feet and an extending small rectangular foundation slab with plane dimension of about 66 feet by 145 feet at plant south-east corner. The TB basemat footprint is rectangular in shape with plane dimension of about 340 feet by 260 feet. The TB is located at the plant south to the RBC and the horizontal clear distance between the two foundations is about 20 feet as shown in Figure 1. The total seismic weight for dynamic analysis of the RBC is about 1,280,000 kips and the total seismic weight of TB including turbine building, electrical room and the common substructure is about 330,000 kips.

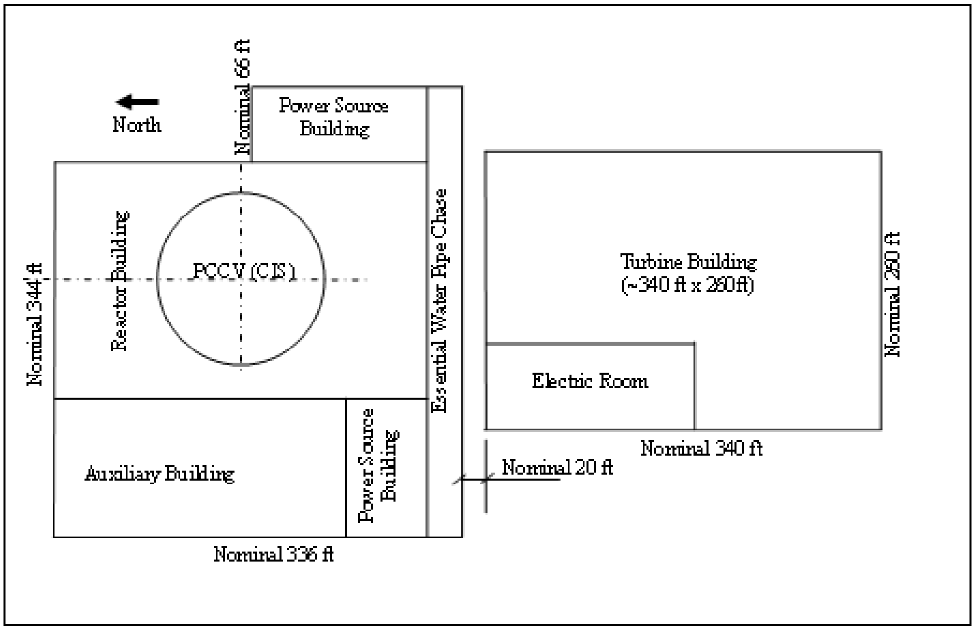


Figure 1 Foundation Layout of the US-APWR Standard Plant Buildings

## ANALYSIS INPUT

### *Soil Profiles*

A total of six generic layered profiles (referred to as free field soils) are developed and used for the design and analysis of the US-APWR standard plant structures. The profiles are denoted as 270-200, 270-500, 560-500, 900-100, 900-200 and 2032-100 where the first number represents the average shear wave velocity in meters per second of the top 30 meters of soil and the second number denotes the overburden depth to bedrock in feet. Profiles 270-200 and 270-500 are relatively soft soil profiles, while profile 560-500 represents stiff overburden. Profiles 900-100 and 900-200 are soft rock profiles. 2032-100 is a hard rock soil profile. Figure 2 shows the small strain shear wave velocity distributions of the six generic soil profiles. Among the six generic soil profiles, four soil profiles, 270-200, 560-500, 900-100, 900-200, are selected to analyze the SSSI effects.

Soil properties that are compatible to the strains generated by the Certified Seismic Design Response Spectra (CSDRS) applied as outcrop motions at RBC foundation level are developed for each of the soil profiles for SASSI analysis. Near field soil elements are also included in the models to simulate the backfills surrounding the basements of the structures and the space between the RBC and TB. The equivalent linear properties of the backfill are proximately CSDRS compatible and are obtained from the assumption that strains of the backfill during seismic excitations are equal to the free soil strains compatible to the CSDRS.

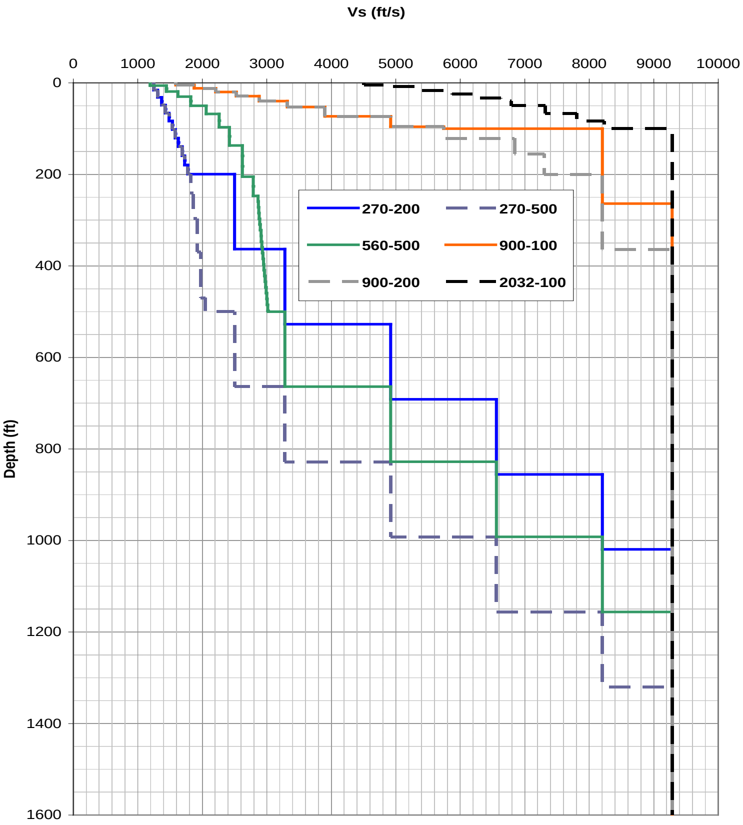
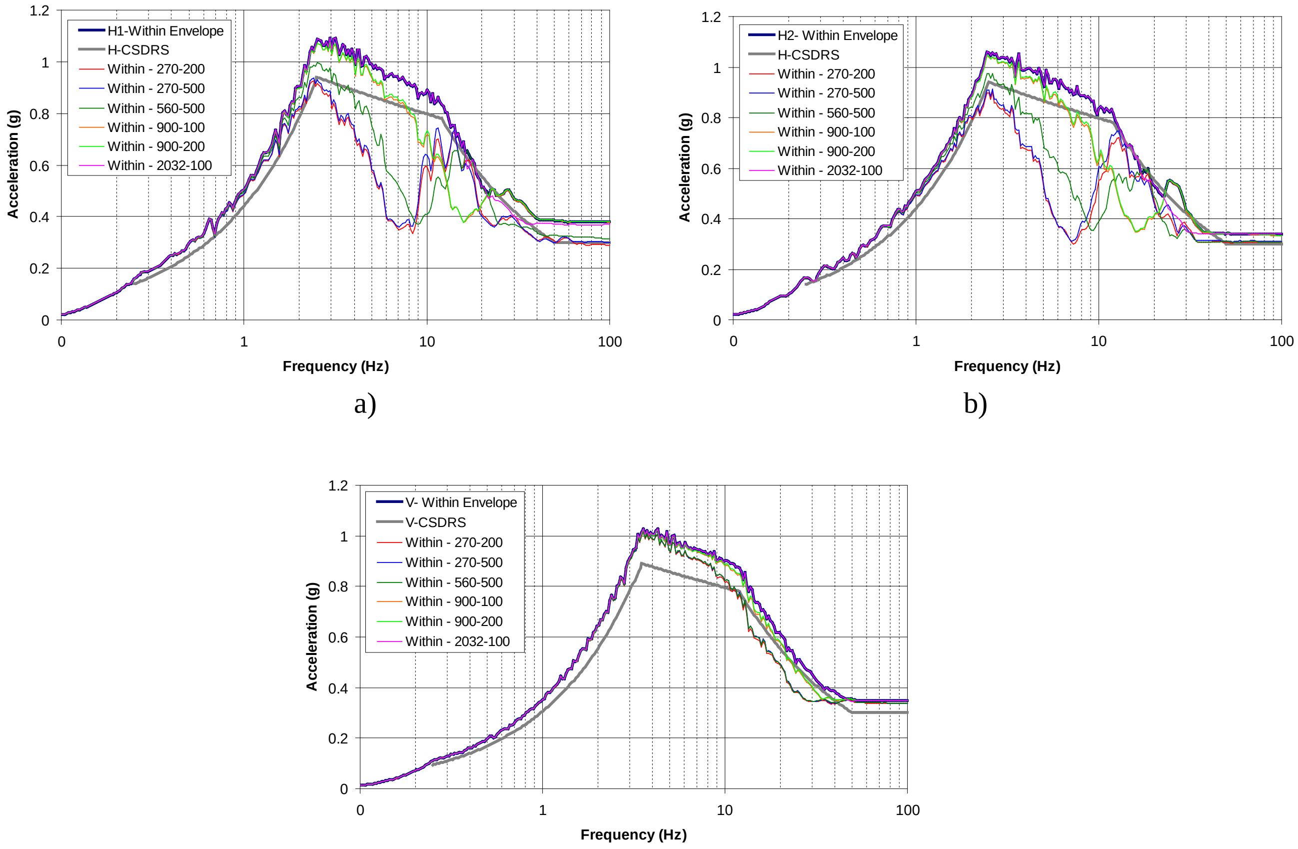


Figure 2 Shear Wave Velocity Distributions of the Six Generic Soil Profiles

## *Input Control Motions*

US-APWR uses enhanced Reg. 1.60 spectra as the CSDRS. A set of three regulatory compliant acceleration time histories (H1, H2, and V) that are compatible to the CSDRS are developed for seismic time history analysis. The H1, H2 and V time histories are used as input for the Plant North-South (NS), East-West (EW) and Vertical directional earthquake excitations, respectively. The CSDRS are applied as outcrop motions at the RBC foundation bottom level. The design basis models for the RBC and TB consider foundation embedment effects by directly analyzing the structures as embedded structures. SASSI program requires within layer motions as input control motion if the structure is analyzed as an embedded structure. Therefore, within motions that are consistent with the CSDRS are developed through full column SHAKE type 1-D analyses for each of the soil profiles. Each set of within motion includes two horizontal and one vertical motion. Figure 3 presents the 5% damped response spectra of the within motion for each soil case and their envelope in comparison with the corresponding CSDRS. The within motion usually is deficient in components of the frequency of the soil column above, however, as shown in Figure 3, there are no deep valleys in the envelopes of response spectra obtained for the six soil cases due to the wide range of soil properties used in the analyses.



a)

b)

c)

Figure 3 5% Damped Response Spectra of the Input Control Motions

## DESCRIPTION OF MODELS

Three-dimensional finite element analysis models of the US-APWR standard plant structures RBC and TB are developed and used in the seismic SSI analyses. The models are developed and validated through various analyses such as 1g static, fixed base modal analysis and harmonic analysis to comply with the regulatory requirements. The two models are combined as an integrated model for SSSI analysis. Figure 4 presents a sectional view of the finite element SSI model for the RBC and Figure 5a presents an isometric view of the RBC model. Figure 6 presents a sectional view of the integrated finite element model (SSSI) for the RBC-TB and Figure 7a presents an isometric view of the integrated RBC-TB model. The models consist of 3-D shell elements, 3-D beam elements, 3-D mass elements and spring elements. The 3-D Shell Elements represent the walls and floors of each building. The 3-D Solid Elements simulate the common basemat, foundation of the PCCV and CIS, near field backfill soils and backfill soils between the RBC and the TB. The 3-D Beam Elements model structural beams, columns, and the piping system of the Reactor Coolant Loops (RCL). The 3-D mass elements represent equipment, water/liquid masses and other applicable loads on the structures. The spring elements model the connections between elements and structural supports.

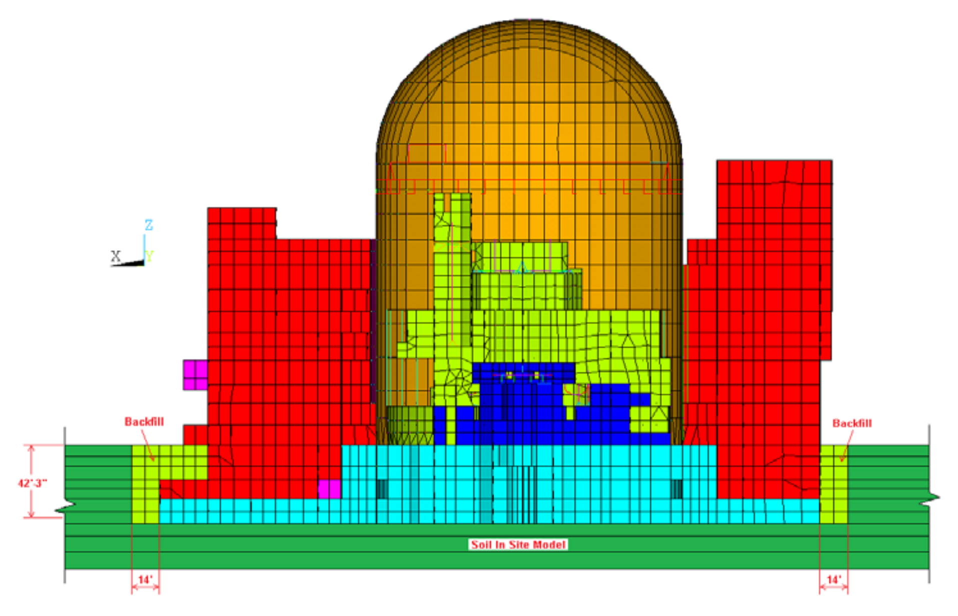
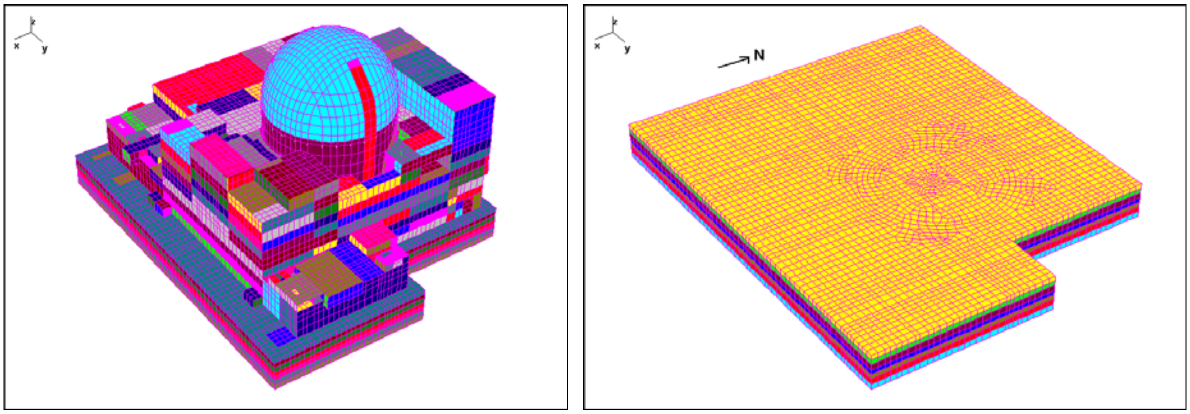


Figure 4   RBC Model Sectional View, Section through the Center Line (looking to the West)



a)   b)

Figure 5   RBC Model Isometric Views   a) Structural Model   b) Excavated Volume

Based on the SASSI formulation, excavated volume is part of the model that represents the free soils replaced by the basement of the structure. Figure 5b and Figure 7b present the excavated volume models for the RBC SSI model and RBC-TB SSSI model, respectively. Brick Solid Elements are used to represent the excavated soils. The TB foundation level is about 15 feet higher than RBC foundation level. Two layers of solid elements are added in the model below the TB foundation to simulate the free field soils in order to create an excavated volume for the RBC-TB SSSI model with a leveled bottom. The corresponding free field soil strain compatible properties are assigned to the two layers of soil elements.

At the bottom and lateral surfaces of the excavated soil volume, the excavated soil and RBC-TB structure/backfill share the same nodes. These nodes, along with the nodes at the top (ground) surface of the excavated soil volume are identified as interaction nodes in SSI and SSSI analyses as required by the

Modified Subtraction Method (MSM). As a result, the excavated volume soil elements share the same mesh size as the structural elements below the plant grade. For RBC model and the RBC portion of the RBC-TB integrated model, at the bottom of the foundation level, the mesh size in the horizontal direction ranges from 6.0 to 9.0 feet, with an average of 6.62 feet in the NS direction and 7.32 feet in the EW direction. In the vertical direction, excavated soil volume mesh sizes are consistent with the soil layering whose thickness varies from 5.38 to 7.00 feet. The excavated volume vertical meshes of the TB portion match the RB portion. In the TB portion, the excavated volume has a nominal horizontal mesh size of 13 ft. The purpose of SSSI analysis is to investigate the effect of the presence of the TB on the RBC. The larger horizontal mesh size in the TB portion is acceptable.

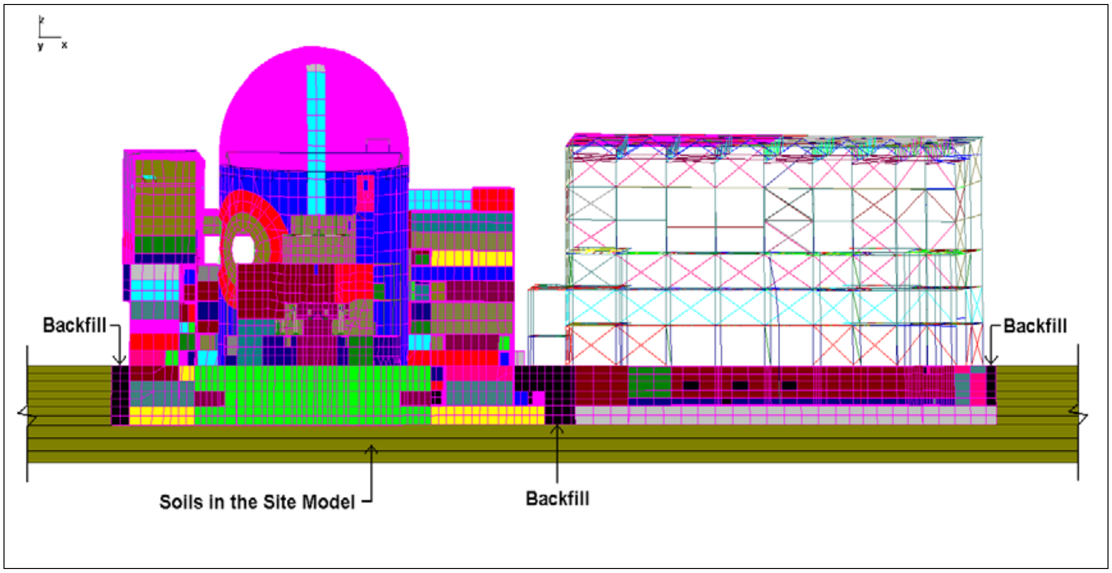
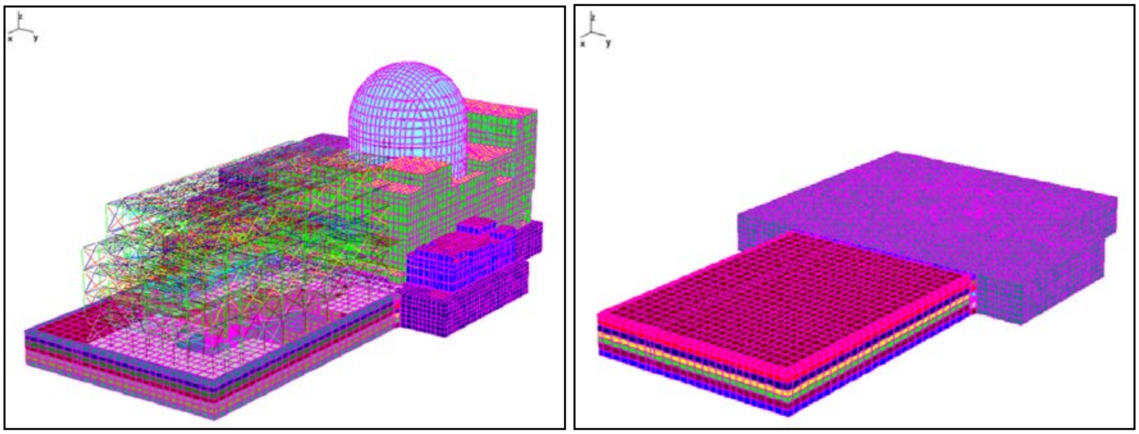


Figure 6 RBC-TB Model Sectional View, Section through the Center Line (looking to the East)



a) b)

Figure 7 RBC-TB Model Isometric Views a) Structural Model b) Excavated Volume

## ANALYSIS PROCEDURE

The SSI analysis of the standalone embedded RBC model and SSSI analysis of the embedded RBC-TB integrated model are performed using ACS SASSI program (Ghiocel, 2012). Two levels of the stiffness for the concrete members are considered for the structural models. The full stiffness (Uncracked) models assign the concrete components with uncracked stiffness and OBE damping values while the reduced stiffness (Cracked) model usually uses half of the uncracked concrete stiffness, and SSE damping values. The comparisons of seismic responses are made for the soil cases 270-200, 560-500, 900-100 and 900-200, which result in a total number of sixteen (16) analysis cases in this study; two structural models combined with four soil profiles, and SSI and SSSI analyses.

The Modified Subtraction Method is used in this study. The exterior surface nodes of the excavated volume are specified as the interaction nodes as required by the MSM (Gutierez, 2011). The numbers of interaction nodes are 7870 and 9648 for the SSI and SSSI model, respectively. To ensure that the method used reasonably captures the dynamic response of the soil structure system, the transfer functions at various locations of interest throughout the RBC are reviewed for anomalies. This review indicates that MSM is a robust method for the models investigated in this paper.

Transfer functions are also reviewed to ensure that the transfer functions are well defined over the frequency range of interest, i.e., they are computed at a satisfactory number of frequency points. In addition, interpolated transfer function curves at characteristic nodes are inspected to ensure no spurious peaks are present. Table 1 presents cut-off frequencies and number of frequency computed for each of the soil cases for both the RBC and RBC-TB models.

Table 1 Computed Frequency

| Soil Cases | Cut-off Frequency (Hz) | Number of Frequency Computed |
|---|---|---|
| 270-200 | 40 | 132 |
| 560-500 | 50 | 152 |
| 900-100 | 50 | 152 |
| 900-200 | 50 | 152 |

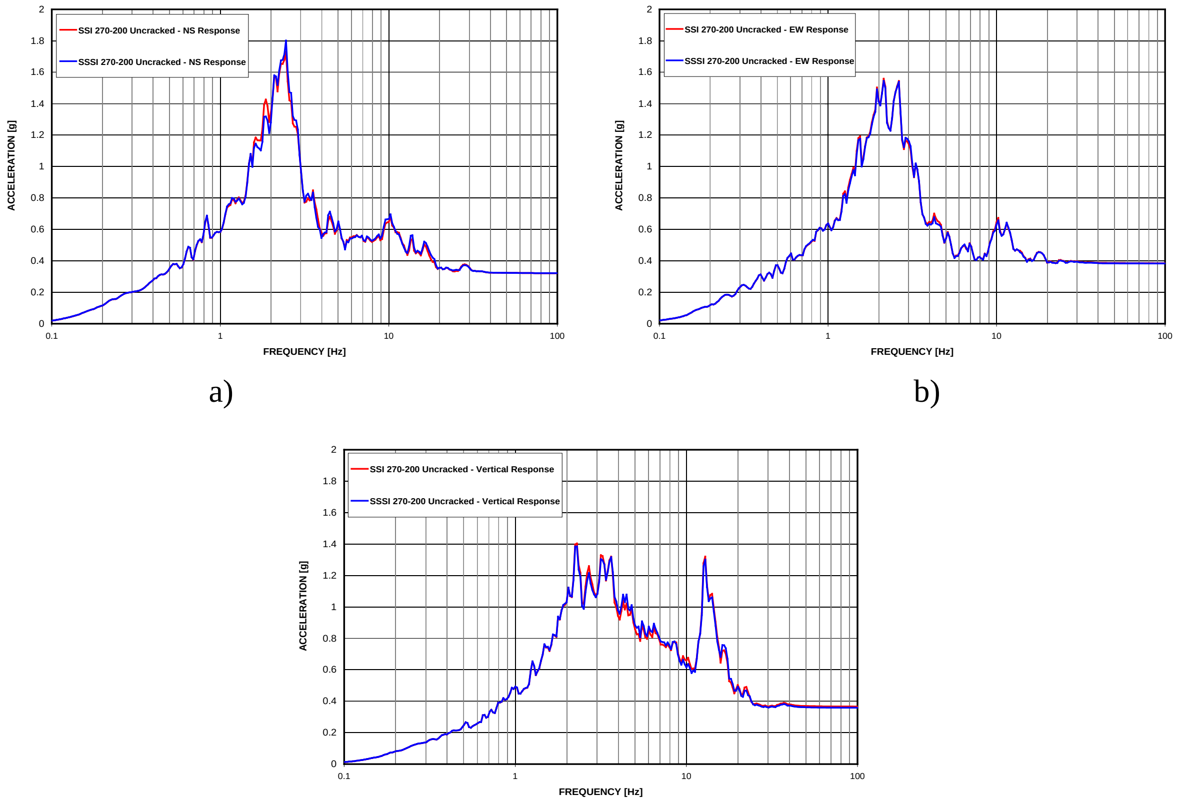
The three components of the earthquake are applied to the models separately and the solutions are superimposed to provide the solution for combined S- and P-wave excitations later to all nodes. The vertically propagating S-waves represent the two horizontal components of the design earthquake motion H1 and H2 that are applied in NS and EW direction, respectively. The vertical component of the design earthquake (V) is represented by vertically propagating P-waves. The same set of seismic input motions for each of the soil cases are considered for the RBC SSI and RBC-TB SSSI analyses. The SSI and SSSI analyses use within motions at the bottom of the RB complex as control motions.

To ISRS from the three-component earthquake for this investigation, the Square Root of the Sum of the Squares (SRSS) method is used to combine response spectrum ordinates from each of the three excitations.

## RESULTS AND DISCUSSION

SSSI analyses are performed for soil profiles 270-200, 560-500, 900-200, and 900-100. The ISRS results of characteristic nodes are compared to the results obtained from RBC standalone SSI analysis with the corresponding soil case. This paper presents typical comparison results, as shown in Figure 8 to 11, for the two typical locations: Reactor Vessel Support (RVS) representing a critical equipment location and RBC South Wall (SW) at ground floor level and PCCV center line representing a typical location in the RBC. Figure 8 and Figure 9 show the comparison at RVS. Figure 10 and 11 compare the results at

SW. Results for 270-200 soil case with uncracked model, and envelope of the four soil cases are presented. In the figures, SSSI responses are denoted as red solid lines while SSI as blue solid lines.



a)

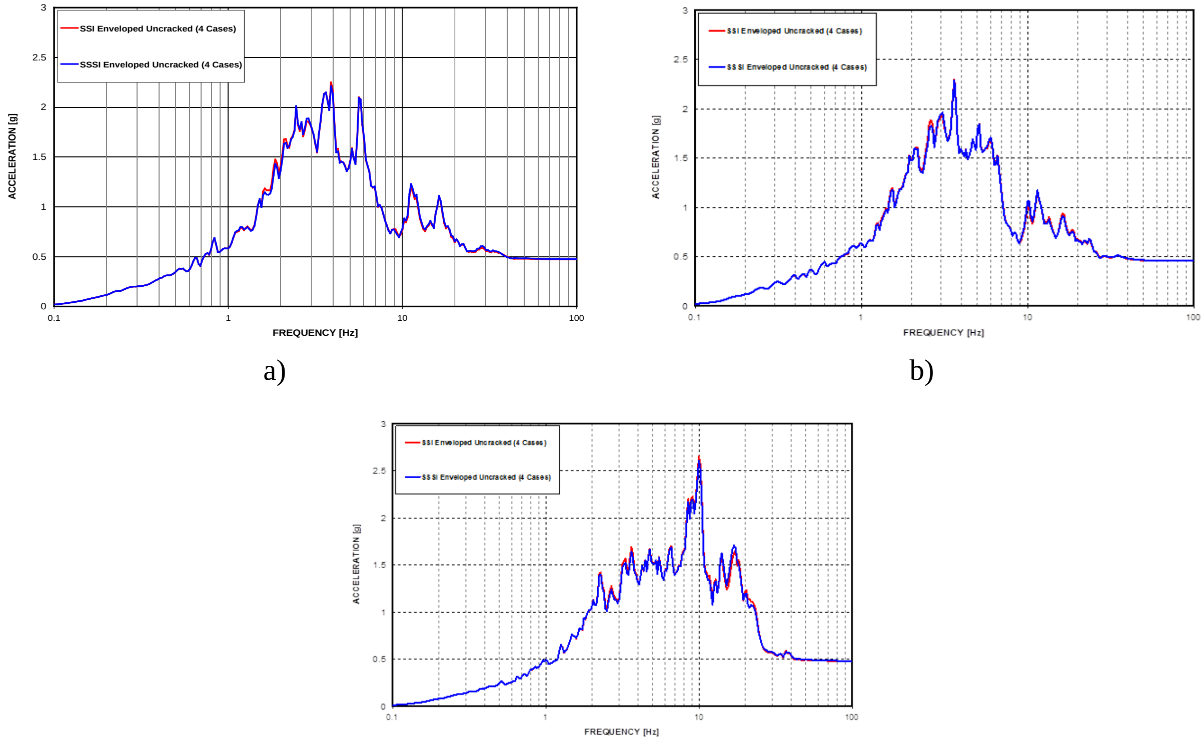
b)

c)

Figure 8 270-200 Response at RVS, a) NS Direction b) EW Direction c) Vertical Direction

It is observed from comparison results of ISRS at various locations that

- The similar effects of SSSI are shown for the models with cracked and uncracked stiffness.
- For the locations in RBC remote from the TB, the SSSI effect tends to slightly reduce the amplitude of the response due to input from NS direction. The NS direction is parallel to the direction that is defined by the two foundations, as indicated in Figure 8a and Figure 9a. The responses to the EW direction input are practically the same for the SSI and SSSI analyses. Negligible differences are observed as shown in Figure 8b and Figure 9b. This observation also applies to the vertical response as shown in Figure 8c and Figure 9c.
- SSSI effects are minor and have only modest impact on the design ISRS for SSCs located close to the TB. Figure 10 and 11 show the comparison of ISRS at a point that is located at the ground floor south wall and the PCCV center line. Compared to the responses at the RVS, minor SSSI amplifications are observed at frequencies higher than 7 Hz.



a) b)

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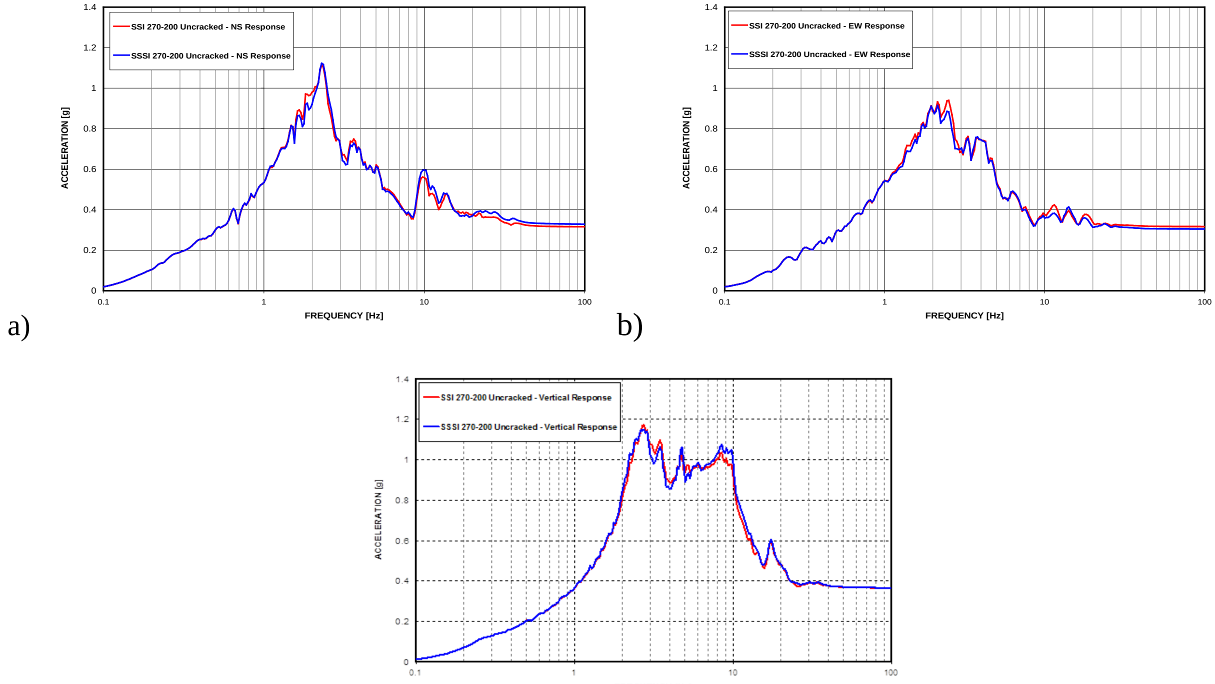
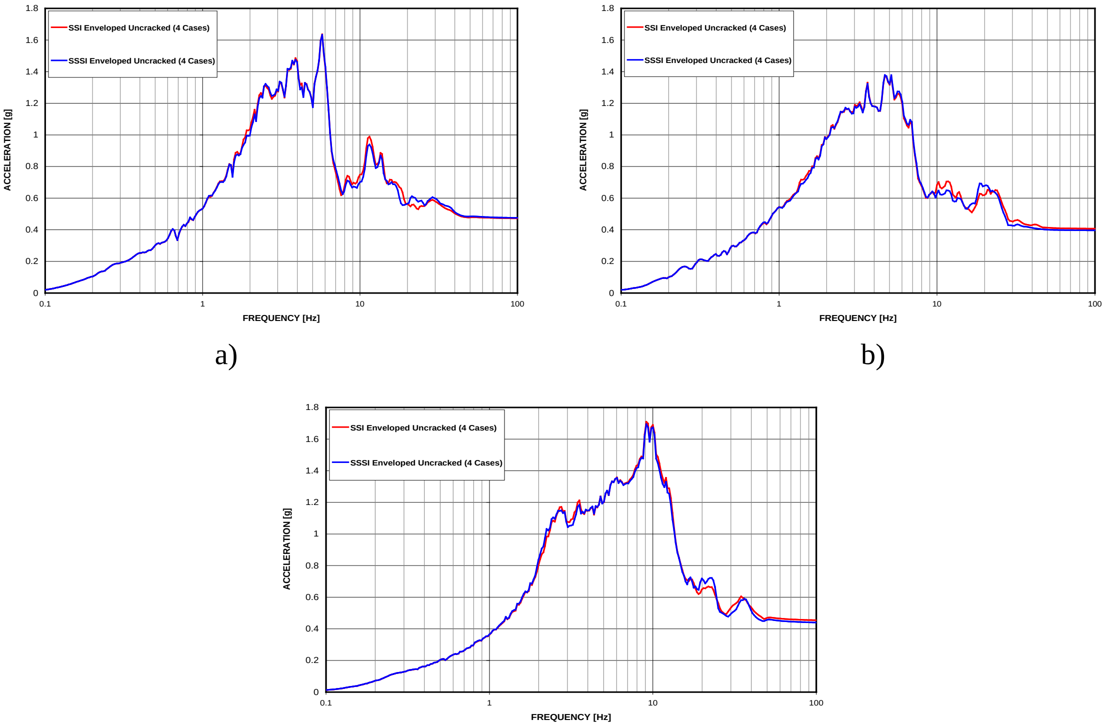
Figure 9 Enveloped Response at RVS, a) NS Direction b) EW Direction c) Vertical Direction



a) b)

c)

Figure 10 270-200 Response at SW, a) NS Direction b) EW Direction c) Vertical Direction



a) b)

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Figure 11 Enveloped Response at SW, a) NS Direction b) EW Direction c) Vertical Direction

## CONCLUSION

Structure-soil-structure interaction effects of US-APWR standard plant buildings, RBC and TB are investigated through dynamic coupling analysis of the soil structure system. The analyses consider foundation embedment effect by directly analyzing the structures as embedded structures. Representative soil profiles from soft soil to rock are analyzed. The effects on RBC are reviewed in terms of response spectra at various characteristic locations and compared to the one obtained from RBC standalone soil structure interaction analysis. The total seismic weight of the RBC (1,280,000 kips) is approximately four times the seismic weight of the TB (330,000 kips) and the foundation bottom level of the TB is about 15 feet higher that of the RBC. The study results indicate that, for soil profiles and structural models analyzed, some minor but insignificant effects are observed for the response of the NS direction, which is parallel to the direction defined by the two foundations and the effects are stronger when the locations are closer to the TB. It is concluded that the SSSI effects of the TB on the RBC in terms of ISRS at characteristic locations are insignificant.

## REFERENCES

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Gutierez, B. (2011). “US Department of Energy Soil-Structure Interaction Report”, Savannah River Operations Offices, DOE, July, 2011