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SEISMIC STRUCTURE-SOIL-STRUCTURE INTERACTION (SSSI) ANALYSIS OF A DEEP WELL AND ADAJENT BUNKER

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INTRODUCTION

This paper presents the results of seismic structure-soil-structure interaction (SSSI) analysis of a deep well and adjacent bunker. The well structure consists of a deep shaft, approximately 1,200 ft in length installed below ground surface and attached at the top to a partially embedded well head building. A surface-supported bunker structure is also located adjacent to the well structure. The well is constructed with different horizontal layers of steel and cement materials encapsulated by FRP material to provide a seal and water integrity. The FRP has no structural functionality but the stresses and/or strains in this material should remain within tolerable limits to ensure acceptable performance following the postulated seismic event. The site soil response is sensitive to frequencies below 10Hz, which can significantly affect the well structure response as the spectral peak of foundation input response spectra (FIRS) is located below 10Hz. The analysis included several sensitivity studies to evaluate the effects of well embedment depth, mesh size refinement, cement grout cracking, variations in soil properties and FRP performance.

The SSSI analysis was performed using the MTR/SASSI program (2015). MTR/SASSI is an enhanced and significantly improved version of the SASSI program (Lysmer, et al., 1981) with capability to analyse large and complex SSI models (Tabatabaie, 2014). Several advanced features of this program that greatly facilitated performance of the current study included capabilities for modelling different material types, use of automated soil blocks, coupling of the soil and structure models using the glue function instead of incorporating rigid links, and graphical output of the results via graphical user interface.

The information provided in this paper are solely for the sake of scientific presentation and does not represent any specific site or the real-world condition, and as such any potential similarity is disregarded.

METHODOLOGY

The SSSI analysis was performed using MTR/SASSI. The basic method of analysis adopted by SASSI, referred to as the Flexible Volume Method (Tabatabaie, 1982), is based on the observation that solutions to the scattering and impedance problems in the general sub-structuring approach can be greatly simplified if the interactions are considered over a volume rather than a boundary. The FVM is a sub-structuring procedure that uses finite element and complex frequency response methods to solve the dynamic response of SSI systems. In the FVM, the complete soil/structure system is partitioned into two substructures, called the foundation and the structure. In this partitioning, the structure consists of the actual structure model minus the excavated soil model (i.e., the soil to be excavated is retained within the foundation, leaving the soil media as a horizontally layered system). Interaction between the structure and foundation occurs at all excavated soil nodes. With this procedure, the scattering and impedance problems are essentially reduced, respectively, to the site response and point load solutions for a horizontally layered site. This makes it possible to effectively analyze three-dimensional SSI models involving deeply embedded structures, as in the current study.

DESIGN INPUTS

Ground Motions and Soil Profiles

Six sets of strain-compatible soil profiles with associated three-component (two horizontal and one vertical component) ground motion acceleration time histories developed at the free-field ground surface are used as input to the SSSI analysis in the current study. The strain-compatible soil profiles and ground motion time histories were generated as part of the site response analysis assuming vertically propagating compression waves (P-waves) for the vertical motions in the z-direction, and shear waves (SV- and SH-waves) for the horizontal motions in the X- and Y-directions. Because of relatively small footprint of the foundation and low frequency content of the input motions, the effects of incoherent ground motions are not significant, and therefore, were not considered in the current study. Details regarding the performance of site response analysis and generation of time histories are not within the objectives of this paper.

Structural Configuration and Properties

The well shaft extends approximately 1,200 ft below the ground surface and incorporates a partially-embedded concrete well head building at the top. The embedment depth of the well head building is about 11 ft. A concrete bunker building supported at the ground surface is located close to the well structure. Figure 1 shows the well shaft materials and relative location of the well head and bunker buildings. The well head and bunker building basemats are modelled with solid elements and the walls with shell elements. The cement grout sections and steel PIT casing in the well are modelled with solid and shell elements, respectively. Table 1 summarizes the material properties for the well and bunker structures. The shell element thickness varies along the height of the well shaft to accommodate various materials.

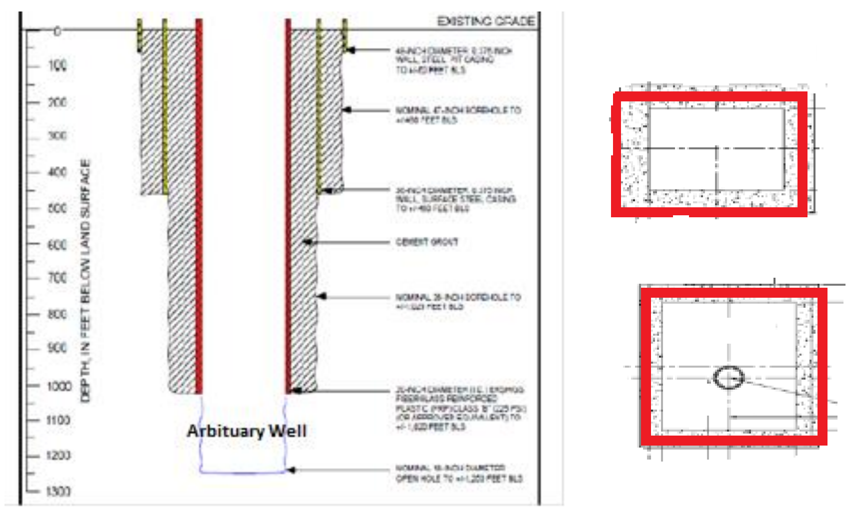

Figure 1 – Different Layers of Well Material and Relative Location of Structures

Table 1: Summary of Structural Material Properties

Material Type	Density (kip/ft^3)	Modulus of Elasticity (kip/ft^2)	Poisson's Ratio
4000 psi concrete	0.15	519,120	0.2
Cement Grout	0.10	259,560	0.2
Typical Steel	0.49	4,176,000	0.3

SSSI Analysis

A total of 96 layers are used to model the upper 465 ft of the well shaft below the ground surface. This depth corresponds to the deepest penetration depth of the steel casing of well shaft. Below this depth, the wall of well shaft is retained by only cement grout having relatively weak strength. Due to relatively flexible section of the grout, it is reasonable to assume that the cement grout is not capable of providing significant resistance against the soil movement below the depth of 465 ft. Therefore, the well shaft model is terminated after extending the cement grout section an additional 3 layers below the depth of 468 ft at which point a uniform halfspace condition is assumed. The minimum cut-off frequency of the input motion varies for different soil cases. For the soft soil case, it is about 7Hz, which is considered adequate. The minimum passing frequency for the SSI analysis is 33 Hz.

The MTR/SASSI program has a feature to generate the excavated soil model (soil block) automatically, which was used in the current SSI analysis. The program also provided a user-friendly graphical user interface (GUI) that was used in preparation and verification of the structure and soil models and properties. The shell elements for different layers of the well were modelled at their actual locations and connected to the soil block using the glue function in MTR/SASSI. With this user-friendly function which allowed two FE models with different nodes to be connected, it was not necessary to use rigid links between the soil block and structure at the interaction nodes, which would have otherwise made the model complicated and prone to numerical problems. Each nodal point on the structure has three translational and three rotational degrees-of-freedom.

<u>3-D Solid Elements</u>**:** The Solid elements are used to model the basemats. No Skewed or distorted elements are used, only 8-node rectangular elements. The material properties for the 4000-psi concrete were assigned to the basemat elements.

<u>3-D Shell Elements</u>**:** The Shell elements are used to model the walls and roof slab with 4000 psi concrete properties. The Shell elements are extended one layer into the basemat to provide proper load transfer between the walls and basemat.

<u>3-D Soil3 Elements</u>**:** The soil block is modelled using the Soil3 elements, which are the same as solid elements except that the properties are obtained from material definitions for the corresponding soil layers. No Skewed or distorted Soil3 elements are used, only 8-node rectangular elements. All the nodes at the bottom of the bunker basemat and for the soil block are defined as interaction nodes, as required for the Direct method analysis in SASSI. In addition, a portion of the foundation soils below the bunker are modelled with the Solid elements and included as part of the structure. All the nodes in this extended soil block are also defined as direct interaction nodes. Although not necessary for the SSSI analysis in SASSI, the use of the extended soil block allows the soil stresses below the basemat to be outputted and examined. It is noted that the actual interaction between the structures are provided through soil media via the subgrade dynamic impedance.

The SSSI analysis was performed for 2 sets of strain-compatible lower-bound soil profiles with the corresponding three-component input motions applied at the free-field ground surface. These soil cases are selected out of a total of 6 soil cases (2 Lower Bounds, 2 Best Estimates and 2 Upper Bounds) developed for the site response analyses. The SSSI analyses are performed assuming vertically propagating P- and S-waves with the input motion specified at the free-field ground surface for the vertical and horizontal motions, respectively. This ensures that the variation of ground motion with depth is essentially the same from the one-dimensional site response analysis and those calculated from the SSI model at sufficient distance away from the influence of the structures. In the SSI analysis, the three components of the input motion are applied simultaneously. The co-directional time history responses from three-directional input are then summed algebraically and used to calculate other response quantities such as ISRS, maximum values of accelerations, stresses, etc.

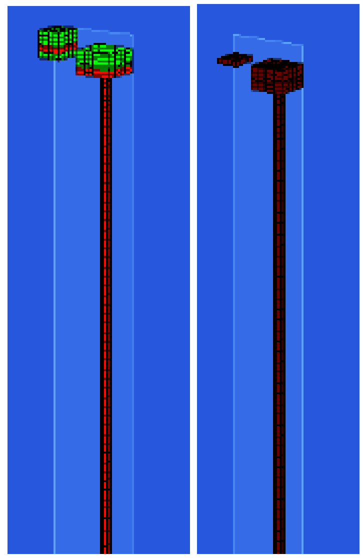

Figure 2: Graphical Representation of Structure and Soil Block Models

ACCEPTANCE CRITERIA

The results of SSSI analysis of the well and bunker structures are validated by carefully examining the behaviour of the structure and soil models using the following criteria:

- Near-zero value of response transfer functions throughout the structure are nearly equal to 1.0.
- Response amplification increases with elevation for the fundamental X- and Y-direction modes for the nodes having the same plan coordinates.
- Reasonable response characteristics such as maximum expected amplification, de-amplification, and corresponding frequency ranges are observed.
- General behaviour of the structure is confirmed by generating and examining the response diagrams from SASSI results.
- Soil column modes obtained from SASSI indicate reasonable agreement with those approximated using the formulae (V_p/4h) and (V_s/4h) for horizontal and vertical directions. Where V_p, V_s and h are the P-wave velocity, S-wave velocity and layer thickness, respectively.

Furthermore, the expected behaviour of the structure at various locations are carefully observed and compared with the response spectra resulting from the analysis. The expected response behaviour of selected nodes is compared to the transfer functions, input motions, and soil properties. The flexural and shear stress data from shell and solid elements are compared with ASCE 4-98 (1998) and NUREG-0800 criteria, which indicated no cracked sections (i.e. the model is found to remain fully un-cracked).

RESPONSE SEPCTRA

Table 2 lists the location of selected nodes for response output in the well and bunker structures. Figure 3(a) compares the 5%-damped acceleration response spectra computed at the top (Node 952, El. 0 ft) and bottom (Node 147, El. -6ft) of the longer wall of well head building in the X-direction for the lower-bound soil case. As shown in Figure 3(a), there is no significant difference between the response magnitudes calculated at the bottom and top of the well head building due to relatively small footprint and stiff nature of the structure. Figure 3(b) compares the 5%-damped acceleration response spectra computed at different elevations in the well structure in the X-direction for the lower-bound soil case. Again, the results show negligible amplification in the well head building from the foundation basemat (Node 147, El. -6 ft) to top of the building (Node 1060, El. 1.5 ft). The response of well shaft itself is significantly lower than the input surface motion, as evidenced by the results of Node 610 located 68 ft below grade.

The results of SSSI analysis in terms of the 5%-damped acceleration response spectra computed at the top of the bunker in the X-, Y- and Z-directions are compared with the corresponding surface motion spectra in Figure 3(c). As shown in Figure 3(c), there is no significant difference between the two results in the horizontal direction due to the SSI effects. In the vertical direction, however, there is significant reduction in the bunker response as compared to the input motion at the surface in terms of the maximum acceleration and spectral amplitudes above 1.5Hz. The reduction in vertical response of the bunker is attributed to kinematic effects due to relatively large stiffness of the building as compared to the soil in the vertical direction.

Table 2: Selected Nodes for Response Output

Node No.	Structure	Description	Elevation (ft)
1060	Well	Top of Well Head Building	1.5
952	Well	On Well Head Building Wall	0
1470	Bunker	Top of Basemat	1
147	Well	Top of Basemat	-6
610	Well	Below Grade Along Well	-68

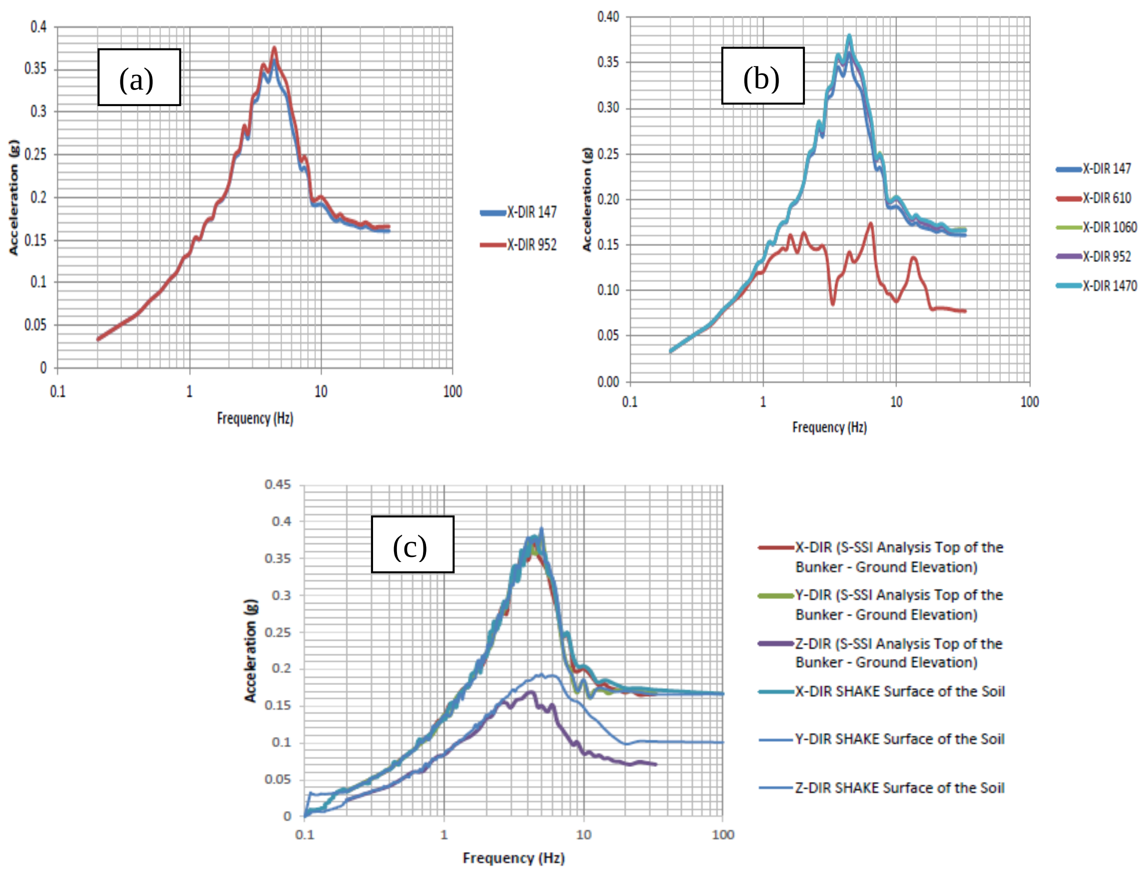

Figure 3: Comparison of 5%-Damped Acceleration Response Spectra

The results of the SSSI analysis in terms of the maximum stresses calculated in the basemats and walls of the well and bunker structures were examined. The results show that all stresses are below the limits of cracking indicating that the structures can be treated as fully un-cracked. In addition, the results of the analysis indicate that the well shaft is moving horizontally in-phase with the soil profile with small relative displacements. This is expected as the motion of the shaft is controlled by the relative lateral stiffness between the soil and well. The relative displacement between the well head and Bunker building basemats calculated across the duration of the displacement time history show comparable results indicating no significant out-of-phase motions.

SENSITIVITY ANALYSIS

Several sensitivity studies are performed to evaluate the significance of well embedment depth, mesh size refinement, cement grout cracking, variations in soil properties and FRP performance, as discussed below.

Well Length Effects: For this analysis, the well shaft is cut off at 47.5 ft below the ground surface and the results in terms of the computed 5%-damped acceleration response spectra at top of the well head building are compared with those of the actual model (see Figure 4). The objective is to have assurance that the building response is not sensitive to the cut-off length of the well, and therefore modelling the well up to 463 ft below the ground surface is adequate. As shown in Figure 4, terminating the well at 47.5 ft below the ground surface has small effect on the well head response in the vertical and horizontal directions.

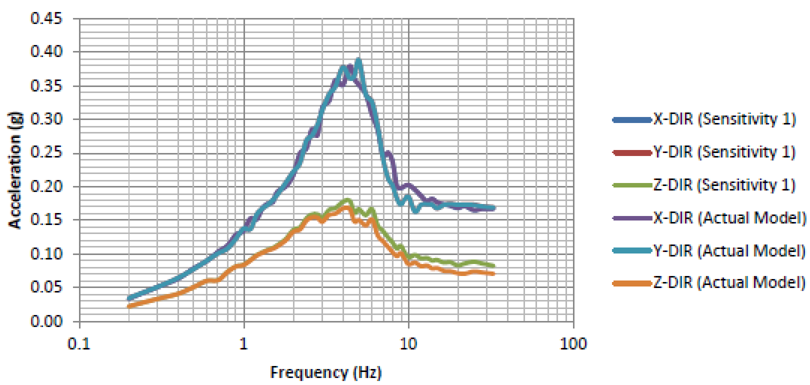

Figure 4: Comparison of 5%-Damped Response Spectra, Well Length Sensitivity Study

Mesh Size Effects: This sensitivity study is performed to evaluate the effect of mesh refinement on the analysis results. For this study, the mesh used for the well model with the shaft terminated at 47.5 ft below ground surface is further refined and the analysis repeated. The new results are then compared with those of the first sensitivity model. Figure 5 shows the model with the refined mesh size together with comparison of the 5%-damped acceleration response spectra computed at the top of well head building from the two models. As shown in Figure 5, there is reasonably good agreement between the results calculated using the denser mesh versus the original mesh model. Figure 6 shows the maximum stress contours for the basemat and cement grout along the well shaft for the two models outputted from the MTR/SASSI GUI. Again, the results show reasonably good agreement.

Based on the above results, it is concluded that the mesh size used in the actual model is acceptable. This confirms the adequacy of the original model mesh size that was selected to control the number of soil layers required to extend the well shaft to a depth of 460 ft below the ground surface.

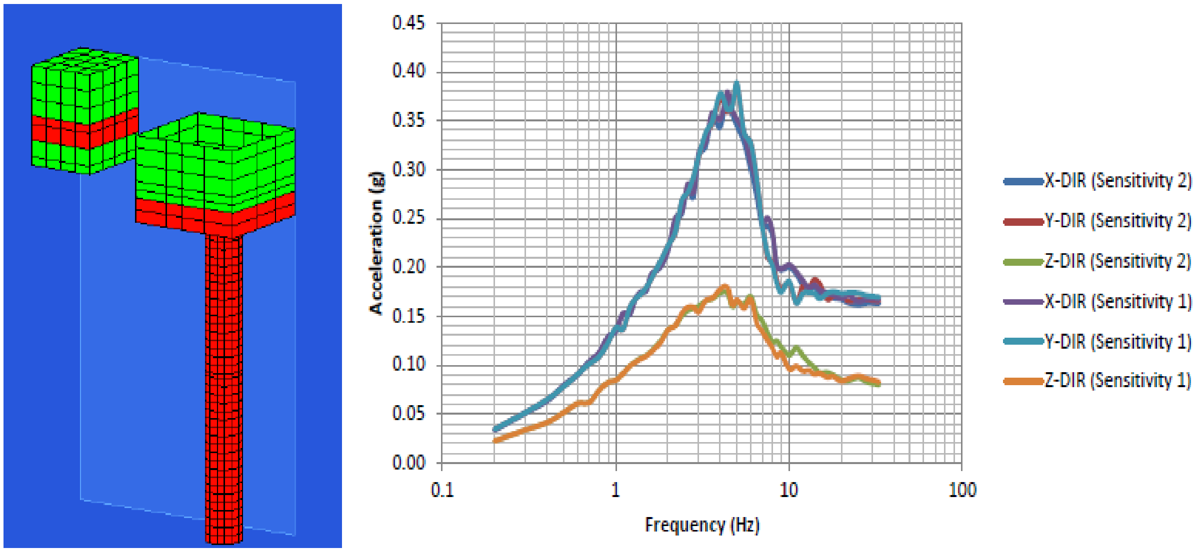

Figure 5: Effect of Mesh Size on Well Head In-Structure Response Spectra

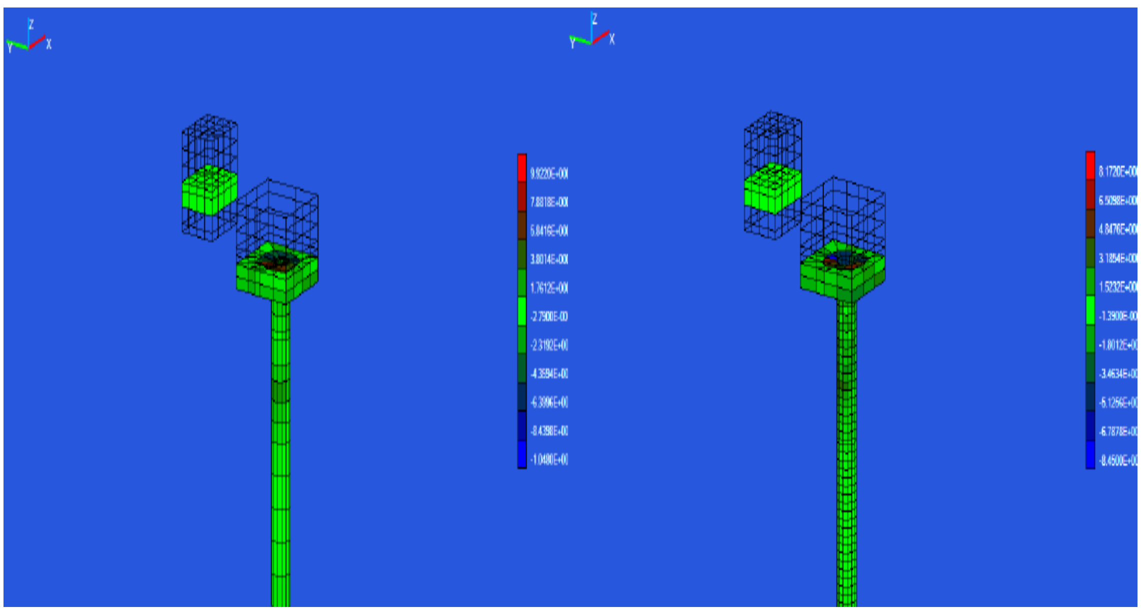

Figure 6: Effect of Mesh Size on Well In-Structure Maximum Stress Contours

Cement Grout Cracking Effects: As discussed above, the model is shown to remain un-cracked. The cement grout is the weakest structural material along the Well shaft. This sensitivity study is performed to evaluate the effects of cement grout cracking. For this analysis, the flexural stiffness of the cement grout sections was reduced by 50% to simulate the cracked sections. The analysis was repeated and the results were then compared with those of un-cracked model. Based on the computed stresses, it is observed that treating the model as fully un-cracked is reasonable. The results show that the stress contours remain essentially the same and the dynamic behaviour of the structure is not affected by the reduced cement grout stiffness.

Soil Profile Variation Effects: This sensitivity study is performed to examine the effect of different soil cases on the analysis results. It is observed that the lower bound soil case is the bounding case with the results enveloping those of the best estimate and upper bound soils.

FRP Performance: The final sensitivity analysis is performed to verify the FRP survival. As discussed above, all the well shaft materials were included in the SSI model except for the FRP. The FRP has no structural functionality and is basically used for sealing the well and providing water integrity. However, to confirm that the FRP survives the postulated seismic event, it was added to the refined mesh model with the actual properties and the analysis was repeated. The calculated normal and shear stresses in the FRP were then compared with the allowable values. In general, it was found that these stresses were below the acceptable limits and the FRP maintains a significant margin against cracking due its flexibility.

CONCLUSIONS

The seismic SSSI analysis of the deep well and bunker was performed for two out of six sets of strain-compatible soil profiles and corresponding ground motions specified at the free-field ground surface using the MTR/SASSI program. In addition, several sensitivity studies were performed to evaluate the effects of well embedment depth, mesh size refinement, cement grout cracking, variations in soil properties and FRP performance. The following summarizes the conclusions of this study:

- The model remains un-cracked, the sensitivity study indicated that cracking the cement grout has insignificant effect on the dynamic behaviour of the structure.
- The SSSI effects on the response of the well head and bunker buildings are negligible due low frequency content of the input motions, and small footprint and relatively high stiffness of structures.
- In general, the well shaft moves in phase with the soil profile in the horizontal direction with small relative displacements.
- The lower-bound soil is the bounding case and the results envelope those of the stiffer profiles.
- The well length has minor impact on the building responses due to high flexibility of the well shaft. As such, when examining the building structure responses, there is no need to model extremely long narrow shafts beyond certain depth.
- In the SSI analysis, it is critical to perform sensitivity studies by changing the model characteristics and examining the results to ensure that the modelling approach is appropriate and the results are reasonable. The sensitivity analyses are generally unique to each condition.

REFERENCES

ASCE 4-98 (1998), ASCE Standard, Seismic Analysis of Safety-Related Nuclear Structures and Commentary, USA.

Lysmer, J., Tabatabaie, M., Tajirian, F., Vahdani, S. and Ostadan, F. (1981). “SASSI – A System for Analysis of Soil-Structure Interaction,” *Report No. UCB/GT/81-02, Geotechnical Engineering, Department of Civil Engineering, University of California, Berkeley,* USA.

NUREG-0800, US Nuclear Regulatory Commission, Standard Review Plan, Section 3.7.1 Seismic Design Parameters, Rev. 4, USA.

Tabatabaie, M. (1982). "The Flexible Volume Method for Dynamic Soil-Structure Interaction Analysis," *Ph.D. Dissertation, University of California, Berkeley*, USA.

Tabatabaie, M. (2014). “SASSI FE Program for Seismic Response Analysis of Nuclear Containment Structures,” *Chapter 22: on Infrastructure Systems for Nuclear Energy*, John Wiley & Sons Ltd.

MTR/SASSI (2015). “System for Analysis of Soil-Structure Interaction,” *Version 9.4.6.7, MTR & Associates, Inc.*, California, USA.