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(b) Responsible Manager (Print/Sign): C. Defigh-Price *C. Defigh-Price*	**Date:** 03-14-06
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Hanford Double-Shell Tank Thermal and Seismic Project - ANSYS Benchmark Analysis of Seismically Induced Fluid-Structure Interaction in a Hanford Double-Shell Primary Tank

TC Mackey
CH2M Hill, Hanford Group Inc.
Richland, WA 99352
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Hanford Thermal and Seismic Project—ANSYS Benchmark Analysis of Seismically Induced Fluid-Structure Interaction in a Hanford Double-Shell Primary Tank

M. W. Rinker
B.G. Carpenter
F. G. Abatt

January 2006

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In particular, one of the greatest challenges of this project has been the seismic analysis of the double-shell tanks. The project team would like to acknowledge the dedicated effort by M&D Professional Services technical staff in completing this work.

It is also important to acknowledge, that while this report has a PNNL cover on it, all of this work was completed by the technical staff at M&D, including Bruce Carpenter and George Abatt.

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ANSYS Benchmark Analysis of Seismically Induced Fluid-Structure Interaction in a Hanford Double Shell Primary Tank

B.G. Carpenter
F.G. Abatt

February 2006

Prepared by
M&D Professional Services, Inc.
for
Pacific Northwest National Laboratory

Prepared by 2/1/06
B.G. Carpenter

2/1/06
F.G. Abatt

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Executive Summary

M&D Professional Services, Inc. (M&D) is under subcontract to Pacific Northwest National Laboratories (PNNL) to perform seismic analysis of the Hanford Site Double-Shell Tanks (DSTs) in support of a project entitled *Double-Shell Tank (DST) Integrity Project - DST Thermal and Seismic Analyses*. The overall scope of the project is to complete an up-to-date comprehensive analysis of record of the DST System at Hanford in support of Tri-Party Agreement Milestone M-48-14. The work described herein was performed in support of the seismic analysis of the DSTs. The thermal and operating loads analysis of the DSTs is documented in Rinker et al. (2004).

The overall seismic analysis of the DSTs is being performed with the general-purpose finite element code ANSYS[1]. The overall model used for the seismic analysis of the DSTs includes the DST structure, the contained waste, and the surrounding soil. The seismic analysis of the DSTs must address the fluid-structure interaction behavior and sloshing response of the primary tank and contained liquid. ANSYS has demonstrated capabilities for structural analysis, but the capabilities and limitations of ANSYS to perform fluid-structure interaction are less well understood.

The purpose of this study is to demonstrate the capabilities and investigate the limitations of ANSYS for performing a fluid-structure interaction analysis of the primary tank and contained waste. To this end, the ANSYS solutions are benchmarked against theoretical solutions appearing in BNL 1995, when such theoretical solutions exist. When theoretical solutions were not available, comparisons were made to theoretical solutions of similar problems and to the results from Dytran simulations.

The capabilities and limitations of the finite element code Dytran[2] for performing a fluid-structure interaction analysis of the primary tank and contained waste were explored in a parallel investigation (Abatt 2006). In conjunction with the results of the global ANSYS analysis reported in Carpenter et al. (2006), the results of the two investigations will be compared to help determine if a more refined sub-model of the primary tank is necessary to capture the important fluid-structure interaction effects in the tank and if so, how to best utilize a refined sub-model of the primary tank.

Both rigid tank and flexible tank configurations were analyzed with ANSYS. The response parameters of interest are total hydrodynamic reaction forces, impulsive and convective mode frequencies, waste pressures, and slosh heights. To a limited extent, tank stresses are also reported.

The results of this study demonstrate that the ANSYS model has the capability to adequately predict global responses such as frequencies and overall reaction forces. Thus, the model is suitable for predicting the global response of the tank and contained waste. On the other hand, while the ANSYS model is capable of adequately predicting

[1] ANSYS is a registered trademark of ANSYS Inc.
[2] MSC.Dytran is a registered trademark of MSC Software Corporation

waste pressures and primary tank stresses in a large portion of the waste tank, the model does not accurately capture the convective behavior of the waste near the free surface, nor did the model give accurate predictions of slosh heights.

Based on the ability of the ANSYS benchmark model to accurately predict frequencies and global reaction forces and on the results presented in Abatt, et al. (2006), the global ANSYS model described in Carpenter et al. (2006) is sufficient for the seismic evaluation of all tank components except for local areas of the primary tank. Due to the limitations of the ANSYS model in predicting the convective response of the waste, the evaluation of primary tank stresses near the waste free surface should be supplemented by results from an ANSYS sub-model of the primary tank that incorporates pressures from theoretical solutions or from Dytran solutions. However, the primary tank is expected to have low demand to capacity ratios in the upper wall.

Moreover, due to the less than desired mesh resolution in the primary tank knuckle of the global ANSYS model, the evaluation of the primary tank stresses in the lower knuckle should be supplemented by results from a more refined ANSYS sub-model of the primary tank that incorporates pressures from theoretical solutions or from Dytran solutions.

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1.0 INTRODUCTON

M&D Professional Services, Inc. (M&D) is under subcontract to Pacific Northwest National Laboratories (PNNL) to perform seismic analysis of the Hanford Site Double-Shell Tanks (DSTs) in support of a project entitled *Double-Shell Tank (DST) Integrity Project - DST Thermal and Seismic Analyses*. The overall scope of the project is to complete an analysis of record of the DST System at Hanford. The work described herein was performed in support of the seismic analysis of the DSTs. The seismic analysis of the DSTs is part of an overall project to provide an up-to-date comprehensive analysis of record for the tanks.

The overall seismic analysis of the DSTs is being performed with the general-purpose finite element code ANSYS[3]. The global model used for the seismic analysis of the DSTs includes the tank structure, the contained waste, and the surrounding soil. The seismic analysis of the DSTs must address the fluid-structure interaction behavior and sloshing response of the primary tank and contained liquid. ANSYS has demonstrated capabilities for structural analysis, but the capabilities and limitations of ANSYS to perform fluid-structure interaction are less well understood.

Moreover, due to the extent of the overall model and corresponding computer resource requirements, some refinement was sacrificed in potentially important details in the primary tank structure. For these reasons, the overall structural model may be supplemented by a more refined sub-model of the primary tank and liquid system.

The purpose of this study is to demonstrate the capabilities and investigate the limitations of ANSYS for performing a dynamic fluid-structure interaction analysis of the primary tank and contained waste. To this end, the ANSYS solutions are benchmarked against theoretical solutions appearing in BNL 1995, when such theoretical solutions exist. When theoretical solutions were not available, comparisons were made to theoretical solutions of similar problems and to the results from Dytran simulations.

The capabilities and limitations of the finite element code Dytran[4] for performing a fluid-structure interaction analysis of the primary tank and contained waste were explored in a parallel investigation (Abatt 2006). In conjunction with the results of the global ANSYS analysis, the results of the two investigations will be compared to help determine if a more refined sub-model of the primary tank is necessary to capture the important fluid-structure interaction effects in the tank and if so, how to best analyze a refined sub-model of the primary tank.

Both rigid tank and flexible tank configurations were analyzed with ANSYS. The response parameters of interest that are presented are total hydrodynamic reaction forces, impulsive and convective mode frequencies, waste pressures, and slosh heights. To a limited extent, tank stresses are also reported.

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1.1 DISCUSSION

The four tank configurations considered were a rigid tank with a waste level of 422 in., a rigid tank with a waste level of 460 in., a flexible wall tank with a waste level of 422 in., and a flexible wall tank with a waste level of 460 in. The 422 in. waste level is intended to represent a baseline waste level for the Hanford DSTs, while the 460 in. waste level represents a higher level being proposed to increase the capacity of the Hanford AP DSTs. Each of the four configurations was subjected to horizontal and vertical seismic excitation as separate cases. The actual waste levels analyzed with ANSYS are, in some cases, slightly different as described in Section 2.0, but will be referred to as the 422 and 460 in. levels in this section.

The response parameters investigated for the rigid tanks were the total hydrodynamic force components, the convective frequency, and the waste pressures. The response parameters for the flexible wall tanks were those for the rigid tanks plus impulsive frequencies and selected element stresses.

The solution for the rigid tank at the 422 in. level was compared to the theoretical solution for an open top rigid tank with a hinged top boundary condition (although the boundary condition is irrelevant for a rigid tank).

The peak horizontal hydrodynamic force predicted by the ANSYS model closely matched the theoretical value, while the peak vertical hydrodynamic force was 17% greater than predicted by theory. The calculated fundamental convective frequency was slightly less than expected, and the effective damping associated with the convective mode was approximately 17% of critical damping – significantly more than the target value of 0.5%.

The calculated waste pressures and pressure distributions also matched well to theoretical values, except for the waste pressures at the bottom of the tank along the plane of excitation and 45° from the plane of excitation during horizontal excitation that showed a high amplitude low-frequency character suggestive of a convective response. This was not expected and is a deviation from theoretical predictions. The maximum slosh height was approximately 8 in. for the 422 in level, which is significantly less than the 24 in. predicted by theory.

Theoretical solutions are not available for the 460 in. waste level because of the interaction between the waste and the dome curvature. However, comparisons were made to the corresponding solution for a tank at the 460 in. waste level with vertical walls, an open top, and a hinged top boundary condition.

The simulation for the rigid tank at the 460 in. waste level showed that the total horizontal reaction force calculated by ANSYS was 10% greater than predicted by open top theory, and the total vertical reaction force was slightly higher than predicted by theory. The fundamental convective frequency calculated with ANSYS was slightly lower than theoretically predicted for the open top tank, and the effective damping associated with the convective response was approximately 20% of critical damping – significantly more than the target value of 0.5%.

The waste pressures due to horizontal excitation that were predicted by ANSYS agree well with expected values in the middle elevations of the tank waste, but deviate from the open top theory near the bottom of the tank and especially near the waste free surface. At the waste free surface, the maximum dynamic pressures are approximately 15 to 20 times larger than predicted by open top theory and also much larger than predicted by Dytran. These deviations are a general character of the solution as opposed to the Dytran solution where deviations occurred at isolated points in time. That is, the nature of the ANSYS and Dytran solutions is different near the top and bottom of the waste. In the case of vertical excitation, the waste pressures generally agreed well with open top theory, except for the pressures approximately 90 in. below the free surface. This only occurred in the rigid tank configuration and was a result of the contact element stiffness properties between the waste and the rigid tank in the domed area of the tank.

The total horizontal reaction force calculated by ANSYS for the flexible wall tank at the 422 in. waste level was 13% greater than the theoretical value, while the total vertical reaction force was 5% greater than predicted by theory. The response showed a breathing mode frequency of 6.6 Hz and an impulsive mode frequency of 7.5 Hz – both approximately 0.5 Hz higher than theoretical predictions. The calculation of the fundamental convective frequency was not performed separately for the flexible tanks.

According to theoretical predictions, dynamic waste pressures exceed static pressures in portions of the waste implying that negative pressures will be predicted for some elements in the ANSYS model. Because the waste is modeled as an elastic material, negative pressures (i.e. tensile stresses) are supported by the ANSYS model, and are realized in the solutions. The negative dynamic pressures should be interpreted as meaning that the pressure in the waste has dropped below atmospheric pressure. However, the stresses predicted in the primary tank are not affected by the appearance of negative dynamic pressures.

As in the case of the rigid tank at the 422 in. waste level, the waste pressure time histories near the bottom of the tank exhibit an unexpected response characteristic of convective behavior. The behavior of waste pressures near the free surface also appears unnatural and may be due to the development of tensile stresses in the waste elements. This behavior is more pronounced closer to the plane of excitation. The waste pressures due to vertical excitation matched reasonably well with theoretical values, but showed higher dynamic pressures than theoretically predicted.

The impulsive frequency for the flexible tank model at the 460 in. waste level was 6.5 Hz compared to a theoretical value of 6.6 Hz. The breathing mode frequency was 5.7 Hz compared to a theoretical value of 5.5 Hz. The fundamental convective frequency was not re-calculated for the flexible tank. The peak horizontal reaction force is the same as predicted by open top theory and the peak vertical reaction force was 10% greater than the theoretical value. As was the case for the 422 in. waste level, the maximum slosh height was approximately 8 in. for the 460 in level, which is significantly less than the 24 in. predicted by theory.

The calculated waste pressure distributions due to horizontal excitation of the flexible tank at the 460 in. waste level are similar to the solutions to the rigid tank at the 460 in. level in that the pressures near bottom of the waste and especially near the waste free surface are much different than predicted by open top theory. At the waste free surface, the peak dynamic pressures are approximately 15 times greater than predicted by open top theory and also much larger than predicted by Dytran The peak pressures are a general characteristic of the solution, and are not due to isolated peaks. Waste pressures due to vertical excitation agree fairly well with theoretical values, and are conservative in the sense that calculated peak pressures are higher than predicted by theory.

Section 7.0 of this report contains direct comparisons between ANSYS and Dytran solutions for the flexible tank configurations. Both codes predict frequencies that agree well with theoretical values, although the Dytran predictions are generally closer to expected values than the ANSYS predictions. Comparison of the reaction forces from the ANSYS and Dytran models showed that the responses from the models are similar with ANSYS generally being conservative relative to Dytran. At the 422 in. waste level, the ANSYS reaction forces were slightly greater than the reaction force predicted by Dytran for both horizontal and vertical seismic input. At the 460 in. waste level, the horizontal reaction force predicted by ANSYS is the same as predicted by theory and essentially the same as predicted by Dytran. In the case of the vertical reaction forces, somewhat higher peaks are predicted by Dytran than ANSYS.

Both models predict responses that are in good agreement with theoretical solutions. In terms of global reactions on the primary tank, both ANSYS and Dytran appear capable of providing good results. In particular, since the loads into the j-bolts connecting the primary tank to the concrete dome are driven by the overall forces on the primary tank, it appears that a global ANSYS model is sufficient for analysis of the j-bolts and that any sub-model of the primary tank need not contain the j-bolts.

Comparison of a limited set of waste pressures due to horizontal excitation from ANSYS and Dytran showed that at the 422 in. waste level, the waste pressures were very similar near the bottom of the tank. In the middle and upper portions of the waste, the ANSYS solution showed more of a convective response than the Dytran solution. At the 460 in. waste level, the peak pressures near the bottom of the waste are higher in Dytran than in ANSYS. Near the top of the waste, the responses are similar, with ANSYS predicting somewhat higher pressures. The appearance of a convective response in ANSYS is less evident at the higher waste level. At an elevation of 292 in. up from the tank bottom, the pressure predictions are very similar, with the ANSYS response being slightly higher.

Finally, comparisons were made between membrane hoop stress predictions for the ANSYS and Dytran models. It is difficult to draw conclusions from these comparisons because of differences in modeling techniques, mesh resolution in the tank wall, mesh resolution near the tank knuckle, and differences in the elevation of the tank wall element centroids. The two models do give very similar results for membrane hoop stress at the middle elevation of 292 in. up from the tank bottom, with the ANSYS results being slightly higher than the Dytran results. A couple of interesting observations on the hoop stresses are that while the convective response was more apparent in the waste pressures predicted by ANSYS near the free surface at the 422 in. waste level, the convective response is more apparent in the hoop stresses predicted by Dytran at that elevation. Also, the convective response that was observed from ANSYS in the waste pressure time history at 292 in. above the tank bottom at the 422 in. waste level is not readily apparent in the hoop stress time history. That is, ANSYS tends to reflect the convective response in the waste pressures, but not as much in the corresponding hoop stresses.

1.2 SUMMARY

The purpose of this study was to demonstrate the capabilities and investigate the limitations of ANSYS for performing a fluid-structure interaction analysis of the primary tank and contained waste. Together with a parallel study and report documenting the capabilities and limitations of Dytran for fluid structure interaction analysis, the ultimate goal is to determine how to best utilize each program to support a seismically induced fluid-structure interaction analysis of a primary tank.

The results of this study demonstrate that the ANSYS model has the capability to adequately predict global responses such as frequencies and overall reaction forces (see Table 1-1 and Table 1-2.) The ANSYS model is capable of adequately predicting waste pressures in a large portion of the waste, but it did not adequately capture the waste pressures near the near the free surface due to the convective response, nor is the model able to give accurate predictions of slosh heights. On the other hand, the model is suitable for predicting the global response of the tank and contained waste. Some of the inaccuracies in the solution may be minimized by increasing the model resolution, but it appears that the model has inherent limitations in its ability to simulate the convective response of the waste.

Based on the ability of the ANSYS benchmark model to accurately predict frequencies and global reaction forces and on the results presented in Abatt, et al. (2006), the global ANSYS model described in Carpenter et al. (2006) is sufficient for the seismic evaluation of all tank components except for local areas of the primary tank. Due to the limitations of the ANSYS model in predicting the convective response of the waste, the evaluation of primary tank stresses near the waste free surface should be supplemented by results from an ANSYS sub-model of the primary tank that incorporates pressures from theoretical solutions or from Dytran solutions. However, the primary tank is expected to have low demand to capacity ratios in the upper wall.

Moreover, due to the less than desired mesh resolution in the primary tank knuckle of the global ANSYS model, the evaluation of the primary tank stresses in the lower knuckle should be supplemented by results from a more refined ANSYS sub-model of the primary tank that incorporates pressures from theoretical solutions or from Dytran solutions.

Table 1-1. Summary of Frequencies and Maximum Slosh Heights.

Configuration	First Convective Mode Frequency (Hz)		Impulsive Mode Frequency (Hz)		Breathing Mode Frequency (Hz)		Maximum Slosh Height (in)	
	Theory	ANSYS	Theory	ANSYS	Theory	ANSYS	Theory	ANSYS
Rigid 424	0.19	0.184	Rigid	Rigid	Rigid	Rigid	23.7	8
Rigid 460[1]	0.2	0.192	Rigid	Rigid	Rigid	Rigid	24.5	8
Flexible 424	0.19	0.184[2]	7.0	7.5	6.0	6.6	23.7	8
Flexible 460[1]	0.2	0.192[2]	6.6[3]	6.5	5.5	5.7[3]	24.5	8

[1]Theoretical solutions for the 460 in. waste level are based on an open tank with vertical walls and a hinged top boundary condition.
[2]Convective frequency response based on rigid tank.
[3]Based on 452 in. waste level.

Table 1-2. Summary of Global Reaction Forces.

Configuration	Peak Horizontal Reaction Force (lbf)		Peak Vertical Reaction Force (lbf)	
	Theory	ANSYS	Theory	ANSYS
Rigid 424	2.45×10^6	2.52×10^6	1.98×10^6	2.31×10^6
Rigid 460	3.0×10^6	3.29×10^6	$2.11 \times 10^{7*}$	$2.15 \times 10^{7*}$
Flexible 424	7.65×10^6	8.67×10^6	2.18×10^7	2.3×10^7
Flexible 460	1.05×10^7	1.05×10^7	$2.35 \times 10^{7*}$	$2.45 \times 10^{7*}$

*Based on waste level of 452 in.

1.3 CONCLUSIONS

1. The ANSYS model showed good agreement with theoretical results for impulsive and convective frequencies and overall reaction forces and generally tends to over-predict the reaction forces.
2. At the 424 in. waste level, the ANSYS model agreed well with theoretical solutions and with Dytran solutions for peak dynamic waste pressures in the middle third of the primary tank wall, which is expected to be the structurally critical area of the primary tank.
3. At the 460 in. waste level, the ANSYS model agreed well with theoretical solutions and with Dytran solutions for peak dynamic waste pressures except near the waste free surface.
4. The ANSYS model has limitations for accurately predicting the convective response of the waste. That is, the model did not provide accurate predictions of maximum slosh heights and waste pressures at the waste free surface. In particular, the waste pressures predicted at the waste free surface for the 460 in. waste level models are not realistic.
5. Even though ANSYS underestimates slosh heights and has an over-damped convective response, the total reactions were very close to theoretical values.

This observation is consistent with the fact that the convective component of the total horizontal reaction force is small relative to the impulsive component.

6. Although the model had less mesh resolution than desired in the primary tank knuckle, the waste pressures predicted by ANSYS near the knuckle were conservative by approximately 20% relative to both theoretical and Dytran solutions at the 424 in. and 460 in. waste levels.
7. Based on the ability of the ANSYS model to accurately predict frequencies and global reaction forces and on the results presented in Abatt, et al. 2006, a global ANSYS model for the seismic analysis of a DST is sufficient for the evaluation of all tank components subject to the limitations on fluid structure interaction evaluation of the primary tank stated herein.
8. Due to the limitations of the ANSYS model in predicting the convective response of the waste, the evaluation of primary tank stresses near the waste free surface should be supplemented by results from an ANSYS sub-model of the primary tank that incorporates pressures from theoretical solutions or from Dytran solutions. However, the primary tank is expected to have low demand to capacity ratios in the upper wall.
9. Due to the less than desired mesh resolution in the primary tank knuckle, the evaluation of the primary tank stresses in the lower knuckle should be supplemented by results from a more refined ANSYS sub-model of the primary tank that incorporates pressures from theoretical solutions or from Dytran solutions.
10. Based on good agreement between ANSYS, Dytran, and theoretical solutions for global reaction forces, a global ANSYS model is sufficient for analysis of the j-bolts and any sub-model of the primary tank need not contain the j-bolts.
11. Running the simulations at gage pressure lead to some negative (dynamic) pressures (i.e. tensile stresses) in the upper portions of the waste. The negative dynamic pressures should be interpreted as meaning that the pressure in the waste has dropped below atmospheric pressure. However, the stresses predicted in the primary tank are not affected by the appearance of negative dynamic pressures.

2.0 MODEL DESCRIPTION

A simplified model of a Hanford Double Shell Tank (DST) was created and analyzed using version 8.1 of the general-purpose finite element program ANSYS. The verification and validation of the ANSYS on the local computer platform is documented in M&D (2005). The purpose of the analysis was to investigate the fluid-structure interaction behavior for several tank structural configurations, liquid levels and loadings. Results from theoretical solutions are presented and summarized for each of the cases in the body of the report, but the details of the theoretical solutions are left to the Appendices.

The two structural configurations studied include a completely rigid primary tank, and a primary tank with a rigid dome and base, but with flexible walls. Simulations were performed for waste levels of 424, 452, and 460 in. The 424 in. waste level is intended to represent the baseline waste level of 422 in., but is not exact because the waste mesh was constrained to match the pre-existing structural mesh in the vertical direction. The 460 in. waste level represents a proposed increased operating waste level for the AP Farm DSTs. Results from the 452 in. waste level are included because some early runs for vertical excitation and for convective and impulsive frequency extraction that were intended to represent the 460 in. waste level were inadvertently run at 452 in. Because the discrepancy is small and responses to vertical input and free oscillations used for frequency extraction are not highly sensitive to the waste level, these simulations were not re-run at the 460 in. waste level. However, when simulations were performed at the 452 in. waste level, they were compared to theoretical solutions at that waste level. Results from the 452 in. waste level simulations will be clearly distinguished from the 460 in. simulations in the body of the report. However, in the remainder of this section, only the 460 in. nomenclature will be used. Applied loads include gravity loading and seismic loading, with seismic loading applied in the horizontal and vertical directions as separate load cases.

The first configuration studied was a completely rigid tank with a waste depth of 424 in. This case is intended to simulate the response of a rigid tank with vertical walls without significant fluid interaction with the dome. The second case was a completely rigid tank with a waste depth of 460 in. At the 460 in. waste level, significant fluid-structure interaction occurs in the dome under seismic excitation. This configuration does not have a theoretical solution, but it is useful as a comparison to the solution for the flexible tank at the 460 in. waste level.

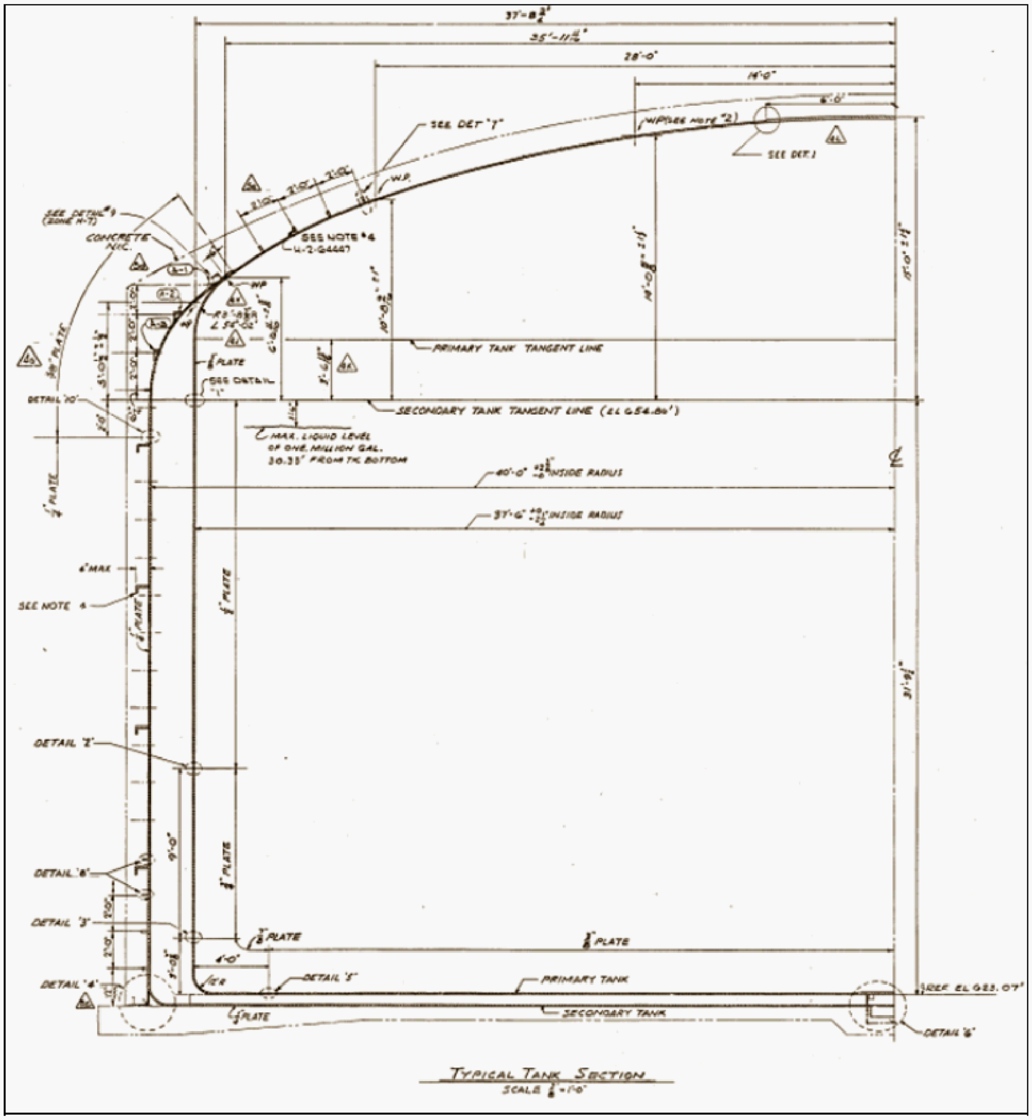
In the third case, the walls of the tank were flexible, and the waste depth was 424 in. This case is intended to simulate the response of a tank with flexible vertical walls without significant fluid interaction with the dome. The fourth configuration studied was a flexible wall tank with a waste depth of 460 in. All four configurations were run for horizontal and vertical seismic excitation independently. The solutions to the first and third configurations at the 424 in. waste level were compared to theoretical solutions from BNL 1995. The results from the second and fourth configurations at the 460 in.

waste depth were compared to the first and third cases as well as to theoretical solution to similar configurations, but no closed form solutions exist for the actual configurations.

2.1 MODEL GEOMETRY

The tank model geometry was based on the AY tank configuration shown in Hanford Drawing No. H-2-64449. The primary tank has a 450 in. radius and the height of the vertical wall is 424 in. The dome apex is 561.5 in. above the bottom of the tank. The models were run using waste depths of 424, 452, and 460 in. An excerpt from Drawing No. H-2-64449 is shown as Figure 2-1.

Figure 2-1. AY Primary Tank Dimensions.



The ANSYS model is a three-dimensional half-symmetry model in which the bottom of the primary tank is supported vertically by a rigid base plate (footing) in contact with the insulating concrete as shown in Figure 2-2. The purpose of the base plate is to provide the vertical support to the bottom of the primary tank model that is provided by the insulating concrete in the actual tank. The entire concrete tank is modeled as rigid to ensure that the top and bottom of the primary tank are excited the same.

As shown in Figure 2-3, the ANSYS model reflects the radius in the primary tank lower knuckle region, however, not all details of the tank lower knuckle region and its support by the insulating concrete have been captured by this simplified model.

Figure 2-2. Plot of ANSYS Model Excluding Waste.

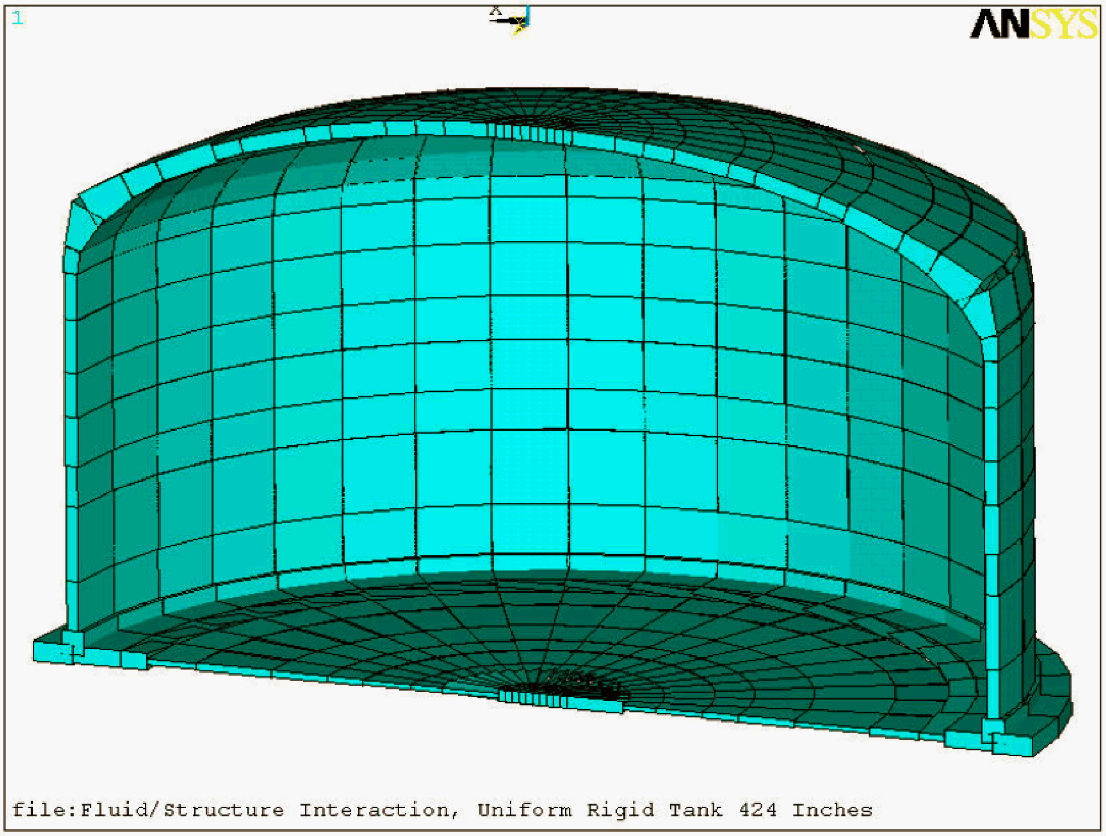
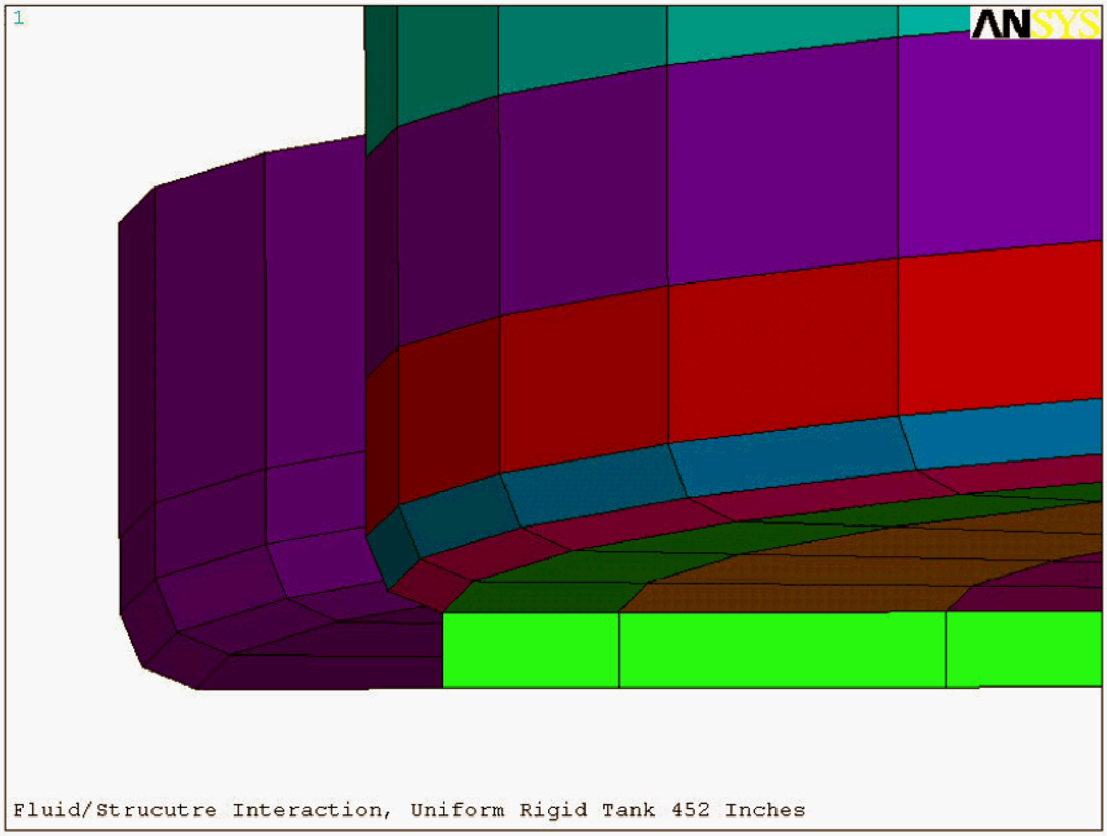


Figure 2-3. Plot of Primary Tank, Base and Knuckle.



The relative height of the waste to the tank for the 424 and 460 in. waste levels is shown in Figure 2-4 and Figure 2-5, respectively.

Figure 2-4. Plot of Tank and Waste at 424 in Waste Level.

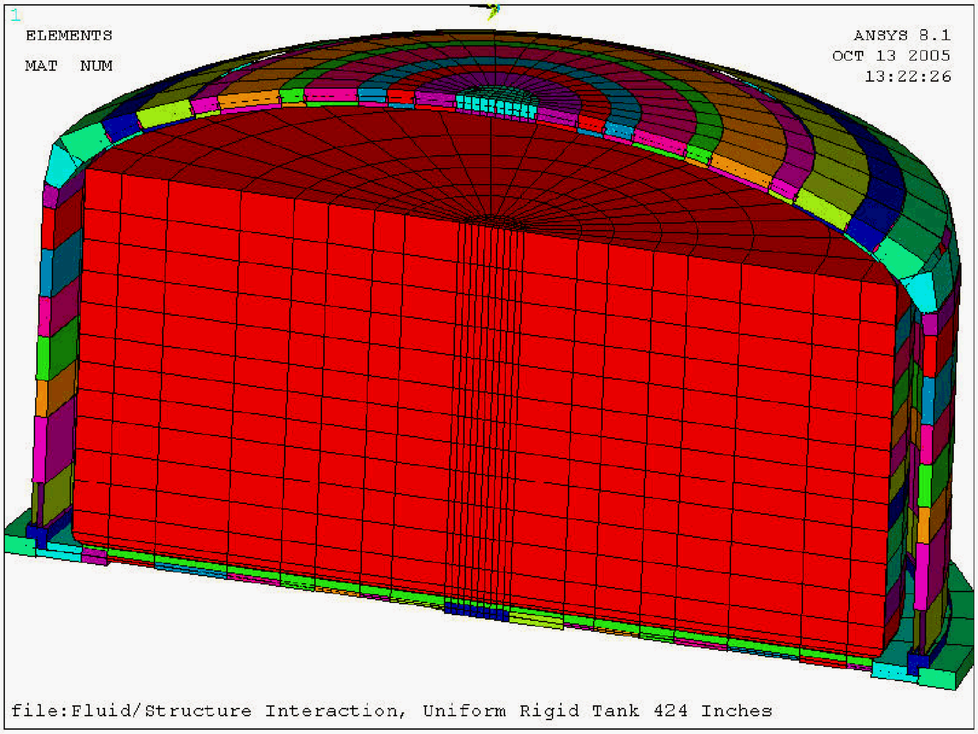
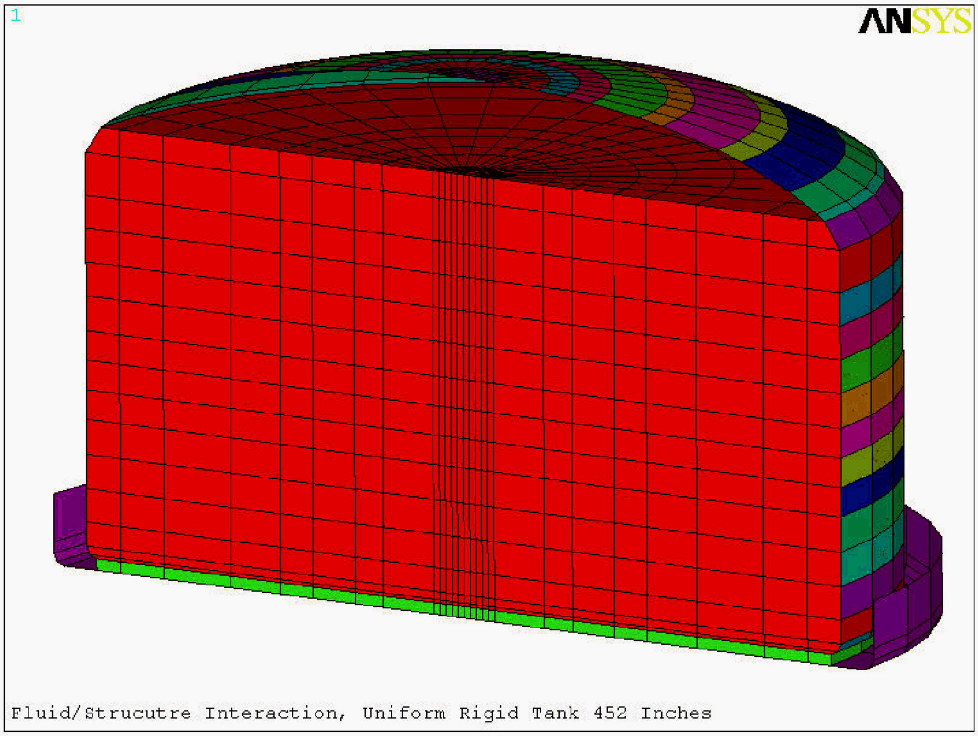


Figure 2-5. Plot of Tank and Waste at 452 in. Waste Level.



Dynamic waste pressures are a function of depth, angular location and radial location of the fluid element. Waste pressures were extracted from all fluid elements in the model, but the results reported focus on waste elements adjacent to the tank wall at 0, 45, and 90° from the plane of seismic excitation (x-z model plane). Contact element numbering for each of the angular locations is shown in Figure 2-6, Figure 2-7, and Figure 2-8 for the 424, 452, and 460 in. waste level models. In the cases of vertical excitation of a flexible tank, waste pressures are also reported for elements at the bottom central region of the tank (see Figure 2-9 and Figure 2-10.

Figure 2-6. Contact Element Numbering for Elements 0, 45 and 90° from the Plane of Seismic Excitation for the 424 in. Waste Level.

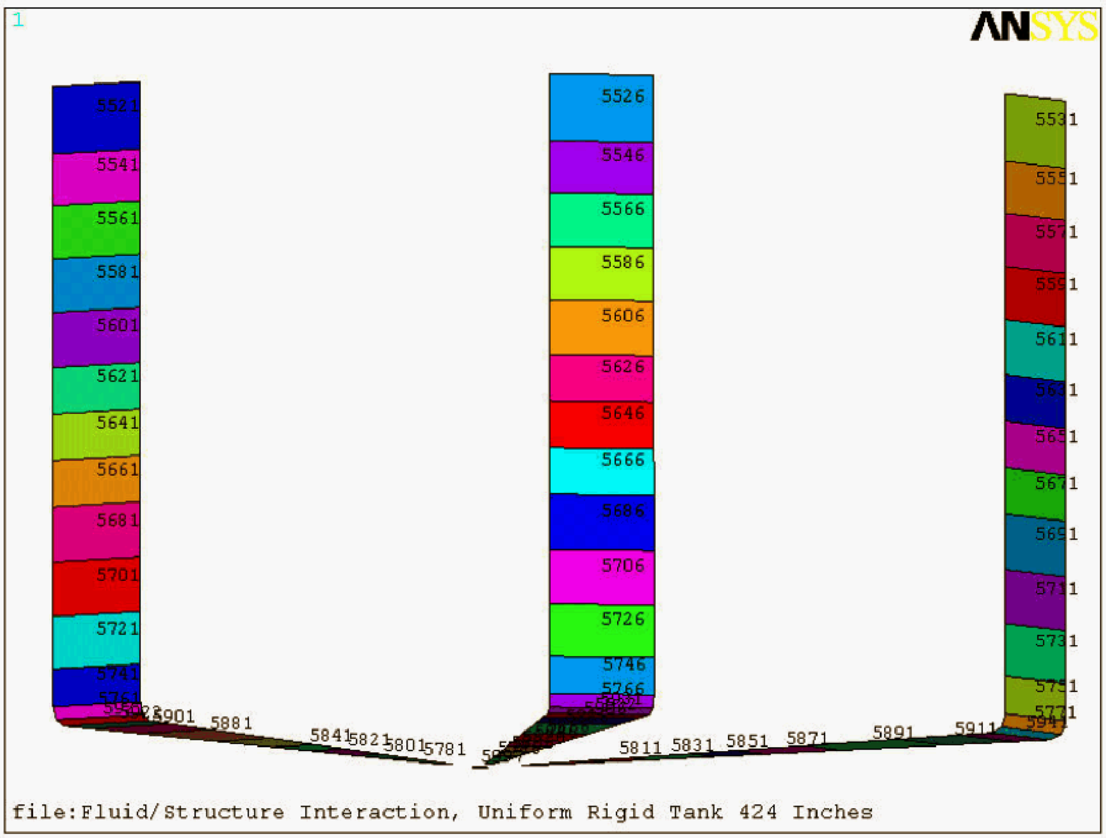


Figure 2-7. Contact Element Numbering for Elements 0, 45 and 90° from the Plane of Seismic Excitation for the 452 in. Waste Level.

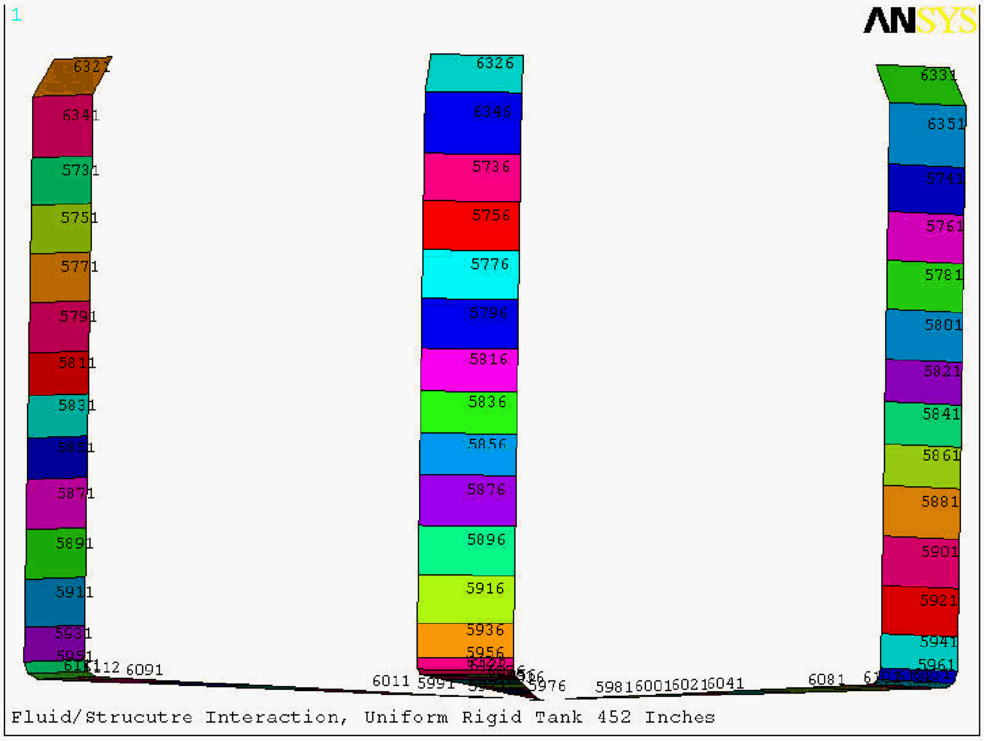


Figure 2-8. Contact Element Numbering for Elements 0, 45 and 90° from the Plane of Seismic Excitation for the 460 in. Waste Level.

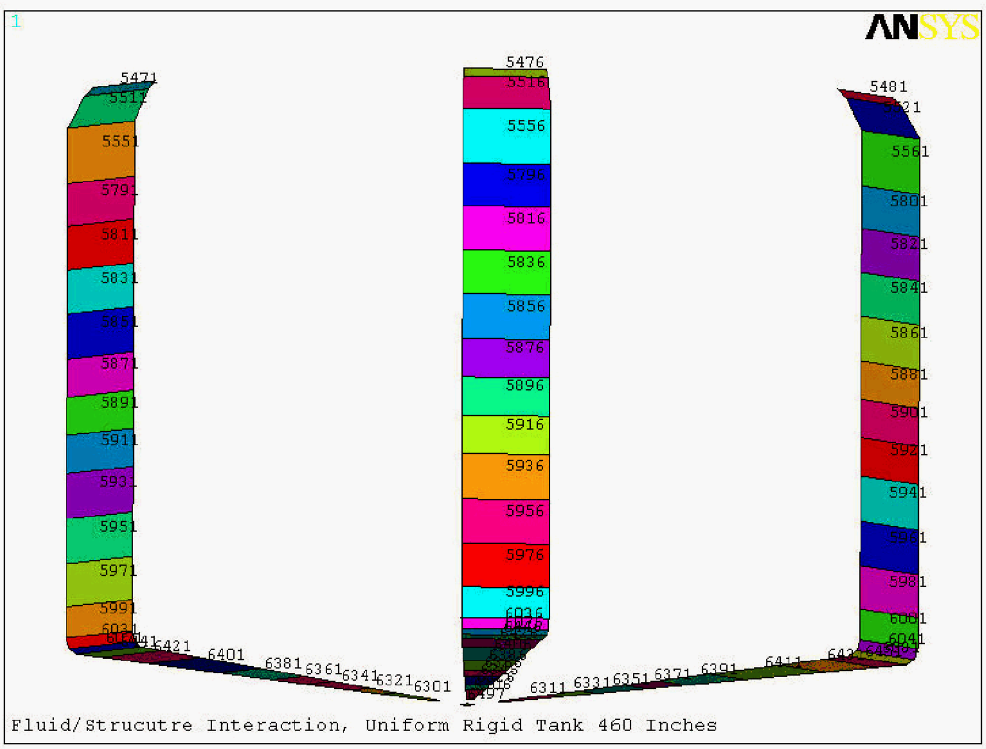


Figure 2-9. Contact Element Number at Bottom Central Portion of Tank for the 424 in. Model.

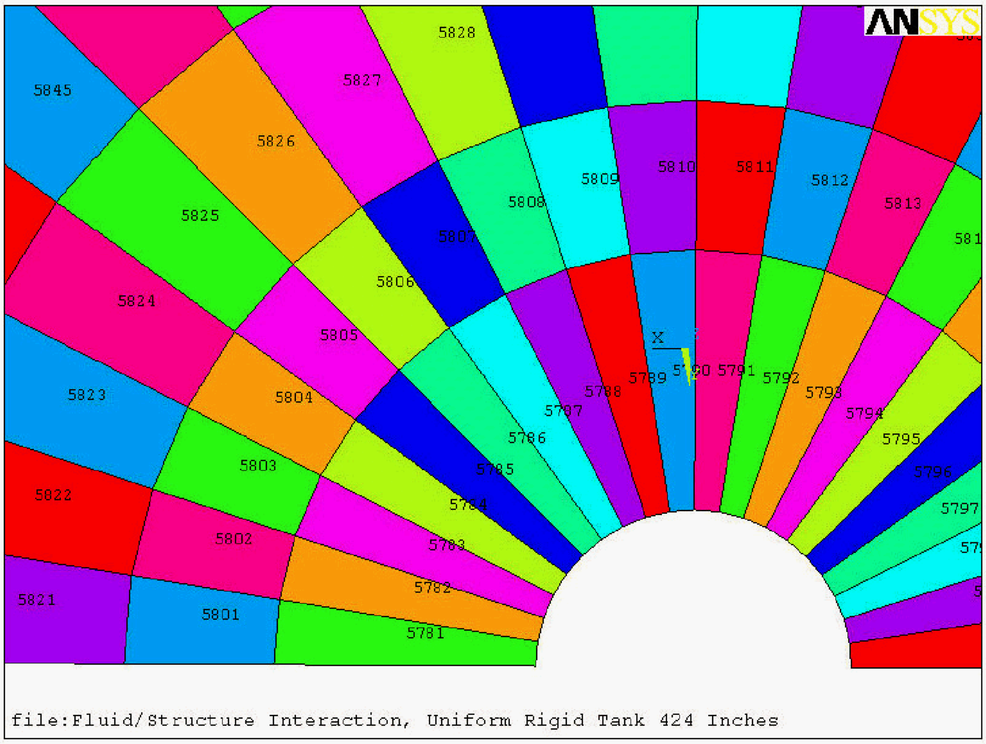
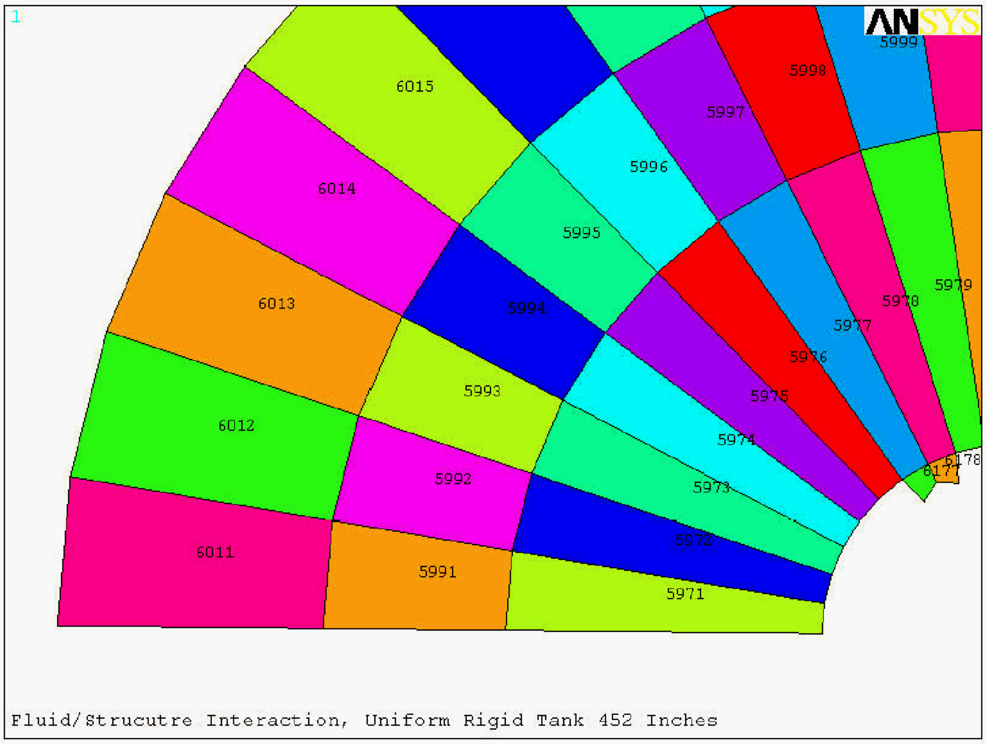


Figure 2-10. Contact Element Number at Bottom Central Portion of Tank for the 452 in. Model.



In the case of the flexible wall model, tank wall stresses were extracted at angular locations of 0, 45, and 90°. The shell element numbering for the θ=0 and θ=45° sets is shown in Figure 2-11, with the elements at θ=0 on the right, and the elements at θ=45° on the left. The numbering for the θ=90° sets is shown in Figure 2-12. The primary tank element number is consistent for all tank flexibility and waste levels considered.

Figure 2-11. Shell Element Numbering for Tank Wall Stress Results at θ=0 and θ=45°.

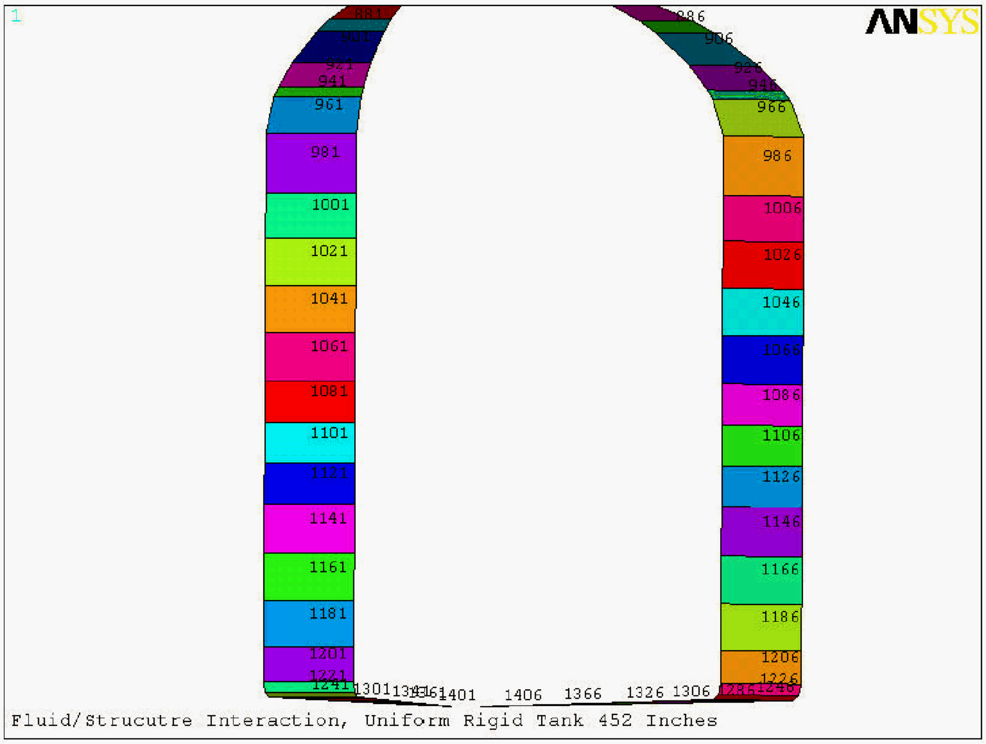
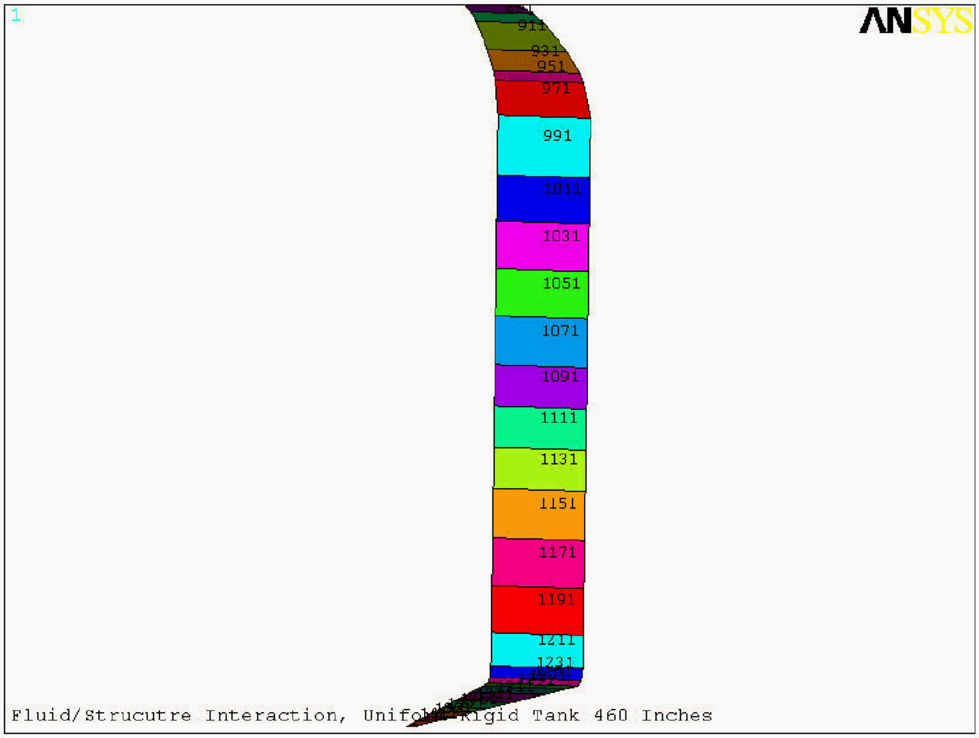


Figure 2-12. Shell Element Numbering for Tank Wall Stress Results at θ=90°.



2.2 MATERIAL PROPERTIES AND ELEMENT TYPES

The primary tank was modeled using SHELL143 elements. In the case of the rigid tank, the complete tank was modeled as a rigid body by increasing the shell thickness and Young's Modulus to be effectively rigid. The concrete tank was included in the model with material properties and thicknesses increased to behave rigidly. A MASS21 element with a very large mass, (greater than 100 times the mass of the waste and tank) was introduced to excite the waste and tank model using force time history input. The large mass is introduced to simulate seismic ground motion and ensure that the ground motion is unaffected by the dynamic response of the model.

In the case of the flexible wall tank, the elastic modulus, Poisson's ratio, and specific weight of the steel walls were set to 29 x 10^6 lbf/in^2, 0.3, and 0.284 lbf/in^3, respectively. The tank wall was assigned a thickness of 0.65 in. which is the approximate average thickness of the lower 2/3 of the AY tank wall. The uniform wall thickness was introduced to simplify the benchmarking model – it is not used for any analysis of record of the primary tank.

The waste is modeled using solid elements (SOLID45) with material properties defined to emulate a liquid. The SOLID45 element was chosen over the FLUID80 element because of limitations with contact options on the FLUID80 element and the fact that the FLUID80 element does not support nonlinear geometry. The material properties for the (solid) waste elements are as follows:

E = 25.92 kip/ft^2
ν = 0.4999
ρ = 0.003294 k-sec^2/ft^2 (=(1.7*0.0624 kip/ft^3)/(32.2ft/sec^2))
Damping = 0
G = 0.216 kip/ft^2

E was calculated based on the Bulk Modulus of water (~300,000 lbf/in^2). Using a value of ν close to 0.5 (0.4999), the value of E can be calculated.

$$\mathrm{B} = E/[3(1-2\nu)]\ or$$
$$E = \mathrm{B}[3(1-2\nu)] = 300{,}000[3(1-2(0.4999))] = 180 lbf/in^2 = 25.92 k/ft^2$$

G can then be calculated based on E and ν, G=E/[2(1+ν)]. For the values shown above, this gives a value for G of 8.64 kip/ft^2. However, because shear stress in a Newtonian fluid is proportional to strain rate rather than strain, a smaller value is used. The value was selected such that the solution remains mathematically stable.

The waste was modeled using a polynomial equation of state (EOSPOL) that requires the initial density and the bulk modulus of the fluid as input. The initial density of the waste was set to 1.59 x 10^{-4} lbf-s^2/in^4 (specific gravity=1.7) for the 424 in waste level models and it was set to 1.71 x 10^{-4} lbf-s^2/in^4 (specific gravity=1.83) for the 460 in. waste level models. The bulk modulus of the waste was set to 305,000 lbf/in^2, which is a typical bulk modulus for water.

Damping values used in this study are based on work done modeling soil column behavior that is reported in Abatt et al. (2006). A combination of alpha (mass dependent) and beta (stiffness dependent) damping are used to develop Raleigh damping. The combination of alpha and beta damping was developed to faithfully reproduce a surface acceleration response of a column of soil excited at the bottom. A value of 0.4 for alpha damping and a scale factor of 40 on material damping were selected to obtain the best response. These values are used here be maintain consistency with the full soil/tank model.

Material damping based on 4% is used for the steel tank. No material damping is applied to the waste material properties

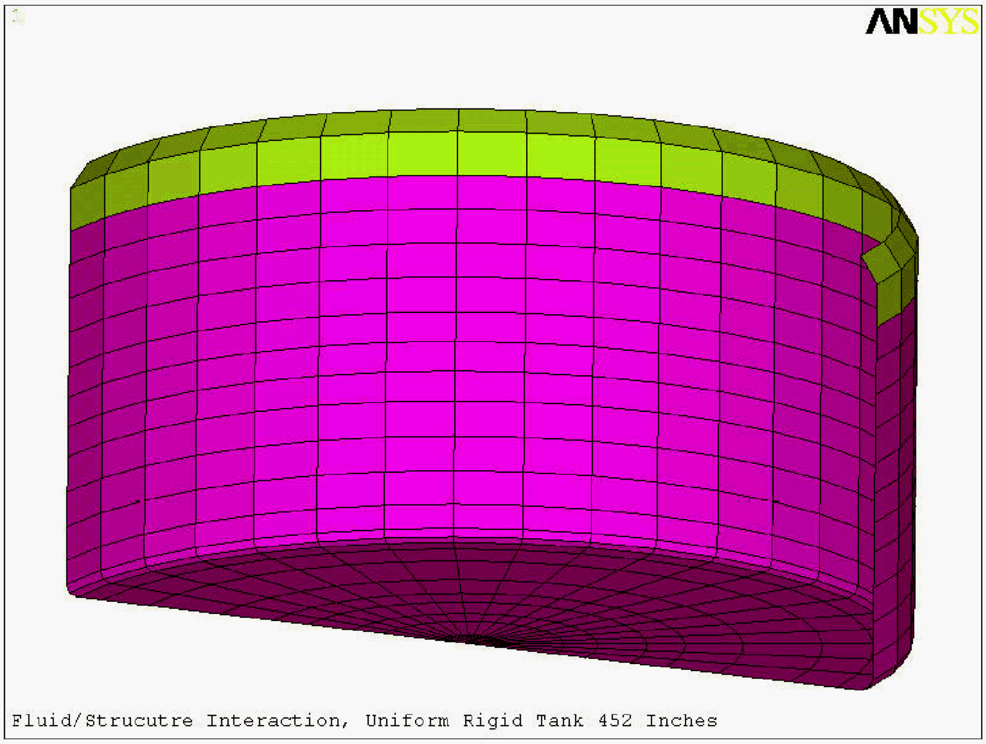
2.3 BOUNDARY CONDITIONS

In the case of horizontal seismic excitation, the rigid regions were free in the x-direction, and fixed in the other five degrees-of-freedom. For vertical excitation, the rigid regions were free in the vertical direction, and fixed in the other five degrees-of-freedom.

2.4 CONTACT INTERFACE CONDITIONS

A combination of CONTA173 and TARGE169 elements were used to model the contact surface between the waste and the tank. Based on ANSYS guidance on modeling contacts between deformable bodies, the target surface is applied to the tank, while the contact surface is applied to the waste. For the 424 in waste level, a single surface was defined for the entire waste to tank interface. The option that always maintains contact between the target and contact elements was enabled for the 424 in waste level. As shown in Figure 2-13, two surfaces were used for the 460 in waste level. The contact surface near the free surface of the waste used a normal contact, i.e., separation can occur. Contacts deeper in the waste used the always in contact option.

Figure 2-13. Waste/Tank Contact Surfaces for the 452 in Waste Level.



2.5 SEISMIC INPUT

The seismic time histories used to excite the tank model were output from a more complete linear ANSYS model of the DST and surrounding soil shown in Figure 2-14, Figure 2-15, and Figure 2-16. The horizontal time history was taken from the dome apex of the ANSYS model, and the vertical time history was taken from the haunch region 90° from the direction of horizontal excitation to minimize rocking effects. The ANSYS model was subjected to simultaneous horizontal and vertical seismic excitation in the absence of gravity. The seismic input for the ANSYS model was applied at the base of the far-field soil shown in Figure 2-16. The extracted time histories consisted of 2,048 points defined at 0.01 second intervals giving seismic records with durations of 20.48 seconds.

Figure 2-14. ANSYS Composite Tank Model Detail (Coarse Mesh).

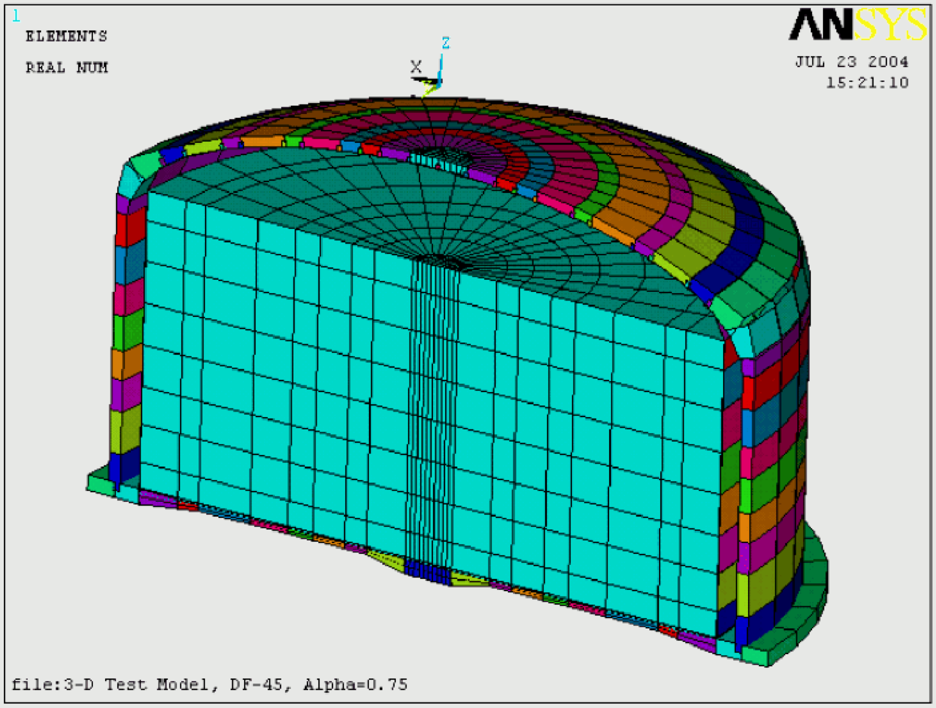


Figure 2-15. Excavated Soil Model Detail for Global ANSYS Model.

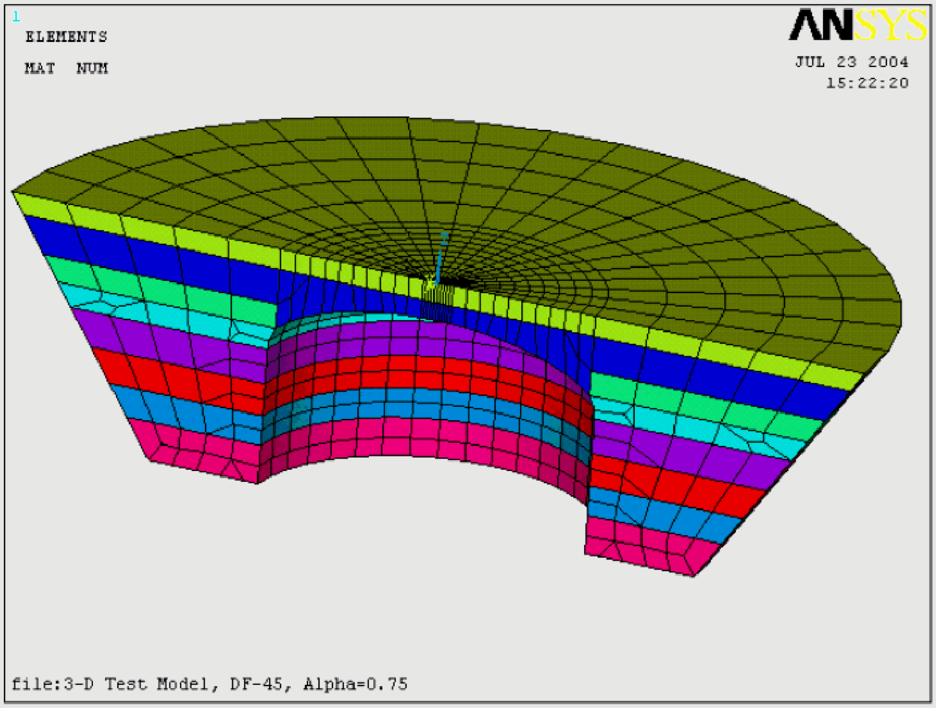
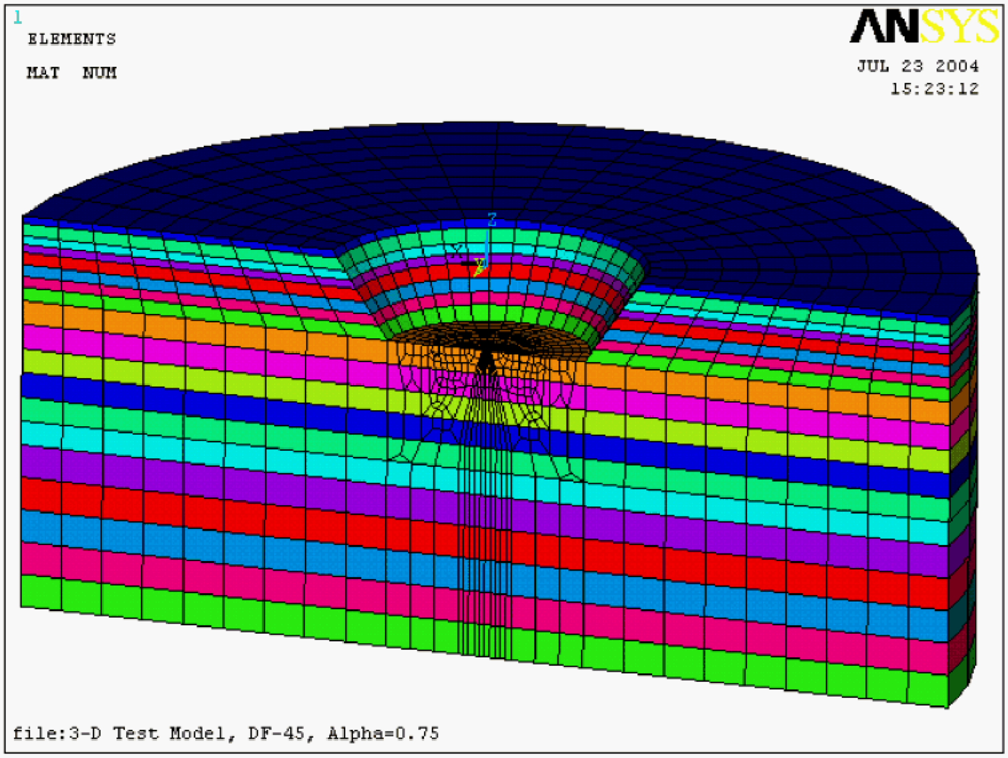
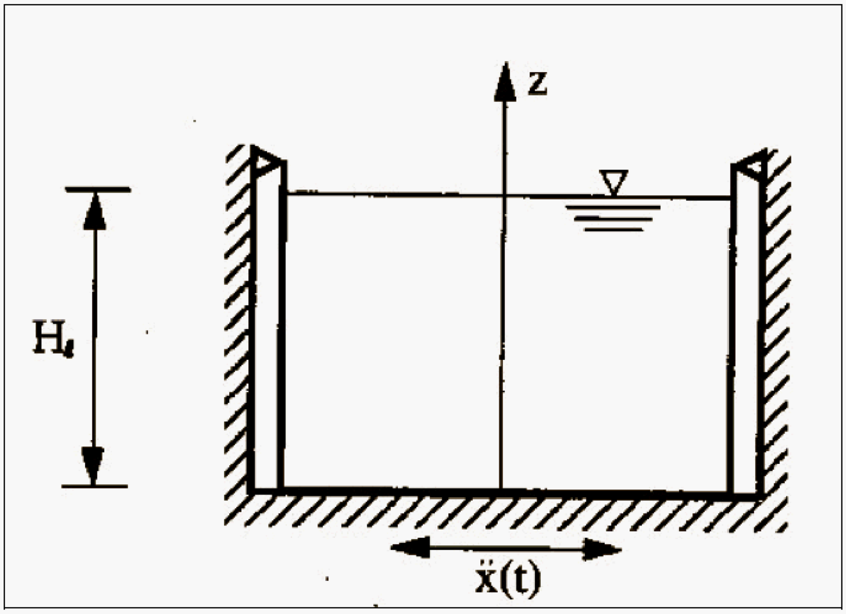


Figure 2-16. Far-Field Soil Model Detail for Global ANSYS Model.



For the completely rigid tank, the whole tank was subjected to the seismic motion. In the flexible tank configuration, the rigid dome and rigid central portion of the tank bottom were subjected to the same input simultaneously. This represents the hinged top boundary condition discussed in BNL 1995 and shown in Figure 2-17.

Figure 2-17. Tank With Hinged Top Boundary Condition per BNL 1995.



The seismic time histories were applied to both the rigid and flexible tank ANSYS models as force time histories on the node of the large excitation mass element. For non-linear problems in ANSYS, an inertial force cannot be applied to the full model. Therefore, to obtain seismic motions, a force time history is applied to a large excitation mass. The mass is large enough such that the response of the waste and tank does not significantly affect the input motion. A force time history is created by multiplying the mass of the MASS21 excitation element by the acceleration time history. For vertical excitation, the mass of the tank and waste must also be included in the force calculation because an inertial gravity force is applied through the analysis.

The horizontal acceleration, vertical acceleration, and the velocity and displacement time histories for horizontal and vertical input are shown in Figure 2-18, Figure 2-19, Figure 2-20, and Figure 2-21, respectively. The 4% damped response spectra for the horizontal and vertical time histories are shown in Figure 2-22. A comparison of horizontal response spectra at damping values of 0.5% and 4%, is shown in Figure 2-23 and Figure 2-24. The plots in Figure 2-24 show that the spectral acceleration near the first convective frequency of approximately 0.2 Hz is 20% greater at 0.5% damping than at 4% damping. That is, in this range of damping values, the convective response is not highly sensitive to damping. The spectra for 0.5% and 4% critical damping are of particular interest because these are the target effective damping ratios for the convective and impulsive response of the tank and waste according to DOE-STD-1020-2002.

Figure 2-18. Horizontal Acceleration Time History Output from ANSYS Model.

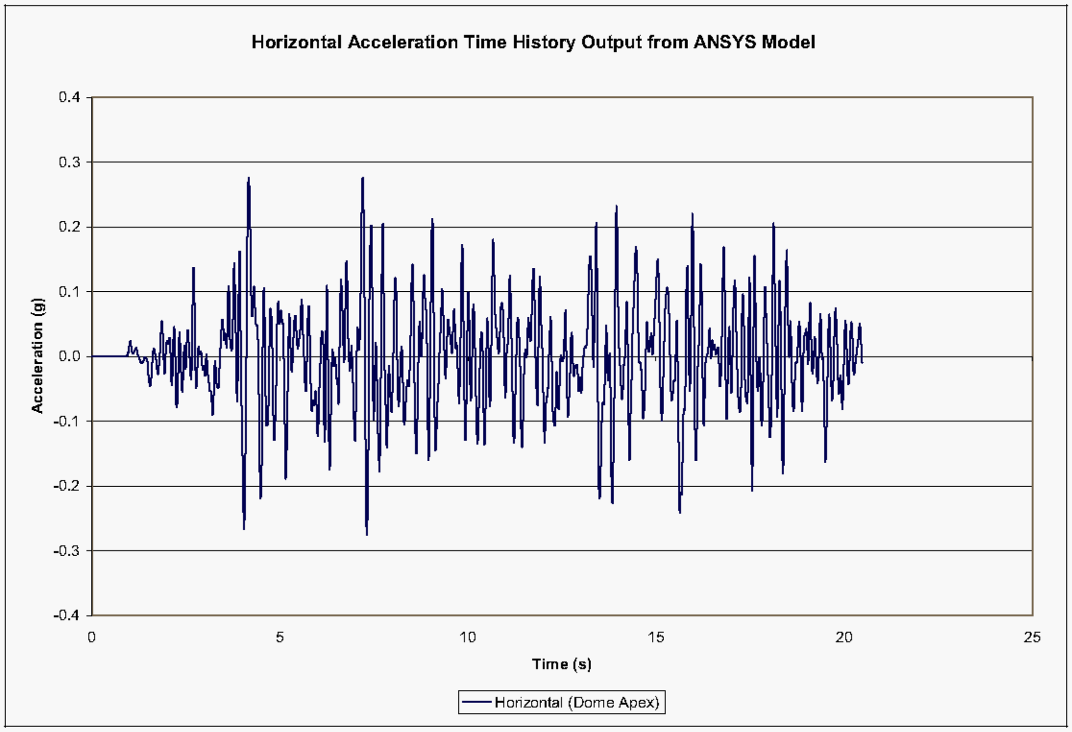


Figure 2-19. Vertical Acceleration Time History Output from ANSYS Model.

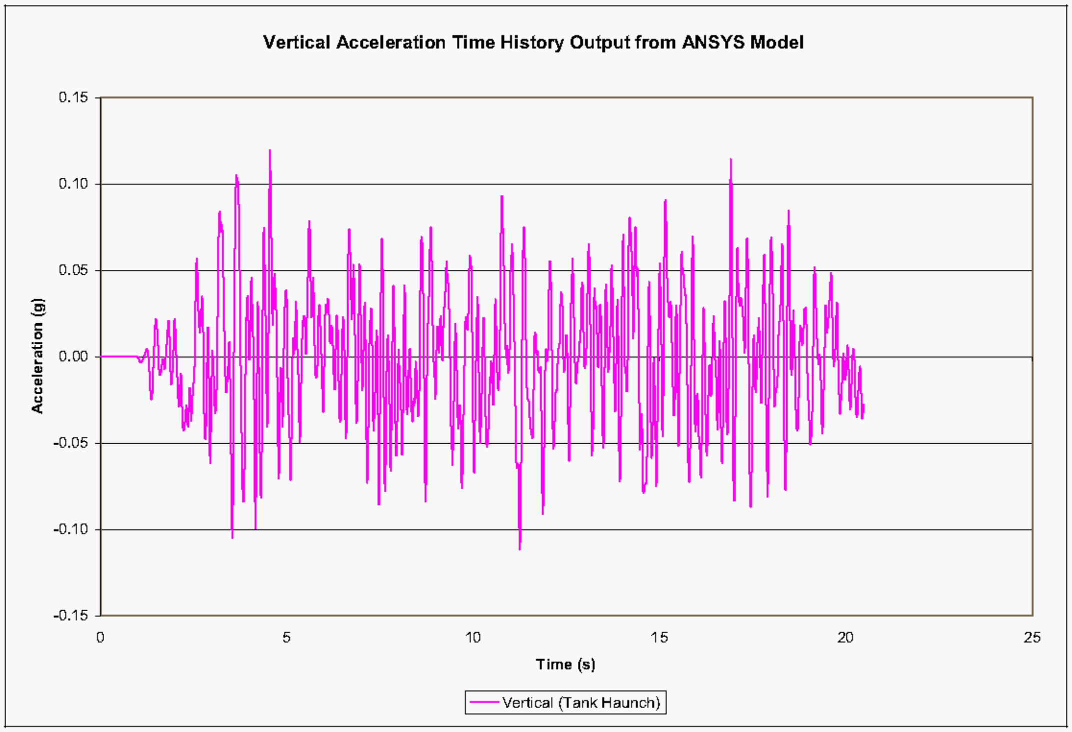


Figure 2-20. Velocity Time Histories Output from Global ANSYS Model.

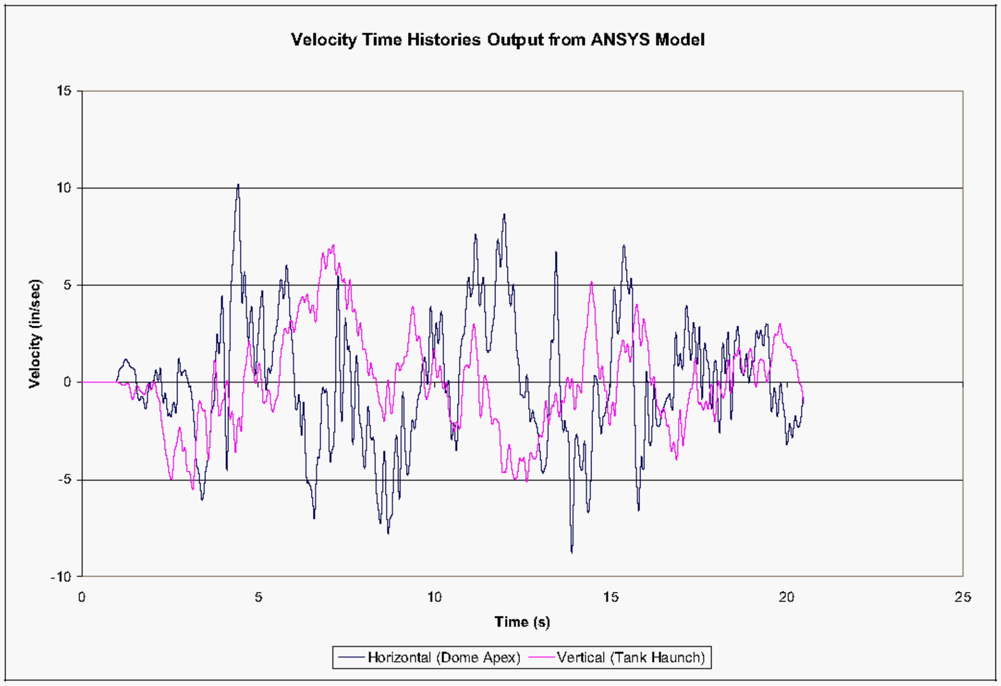


Figure 2-21. Displacement Time Histories Output from Global ANSYS Model.

Figure 2-22. 4% Damped Response Spectra for Acceleration Time Histories Extracted from Global ANSYS Model.

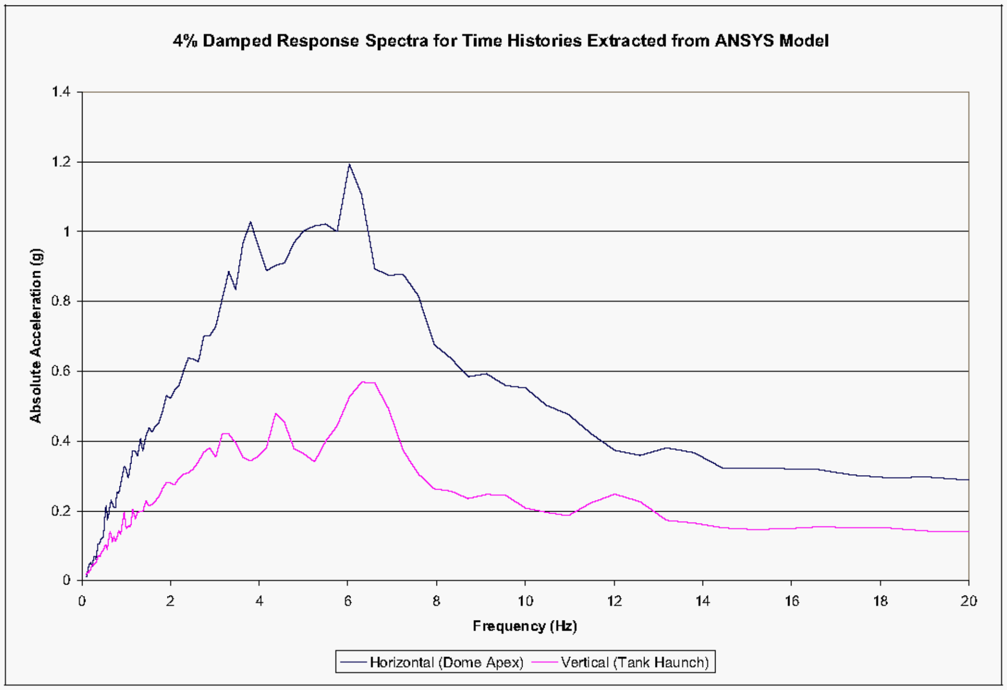


Figure 2-23. Comparison of Horizontal Dome Apex Response Spectra at Different Damping Values.

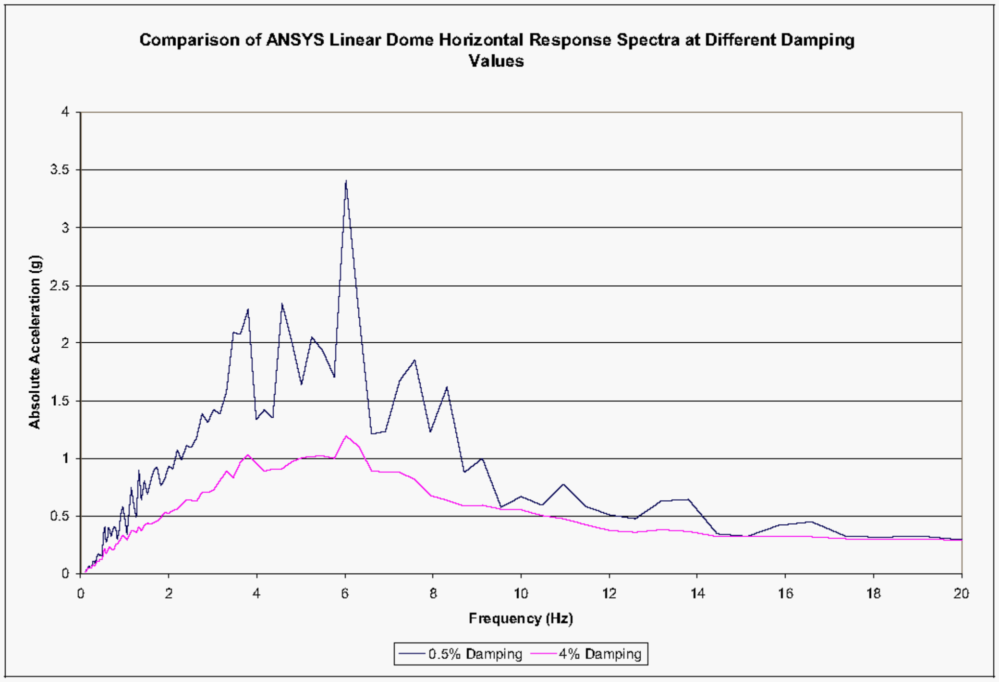
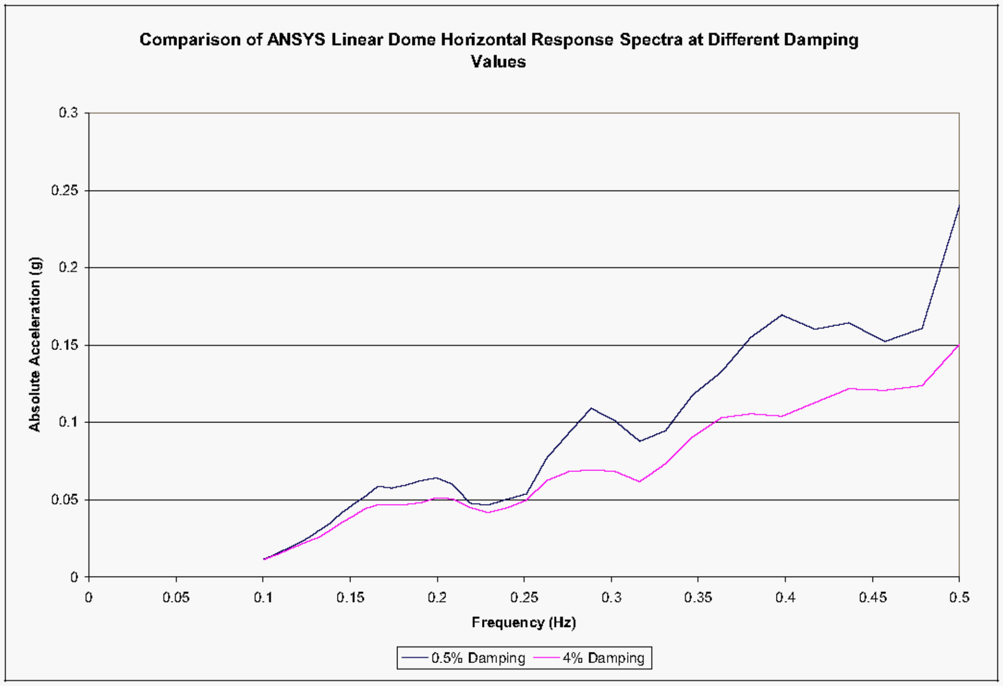


Figure 2-24. Comparison of Horizontal Dome Apex Response Spectra at Different Damping Values for Low Frequencies.



3.0 RIGID ANSYS MODEL AT 424 INCH WASTE LEVEL

The expected hydrostatic pressure at the centroid of the waste elements is easily calculated knowing the vertical location of the waste elements and the initial pressure using the equation $p = p_0 + \rho g \Delta h$, where p_0 is the ambient pressure at the free surface and is set to zero for gage pressure. The expected hydrostatic pressures for the element sets at θ=0, 45, and 90° from the plane of excitation are shown in Table 3-1.

Table 3-1. Expected Hydrostatic Pressure of Waste Elements.

Normalized Height from Tank Bottom (z/H_l)	θ=0 Element No.	θ=45° Element No.	θ=90° Element No.	Hydrostatic Pressure (psi gage)
0.95	5521	5526	5531	1.4
0.85	5541	5546	5551	3.8
0.77	5561	5566	5571	5.9
0.69	5581	5586	5591	8.1
0.60	5601	5606	5611	10.3
0.52	5621	5626	5631	12.4
0.45	5641	5646	5651	14.3
0.38	5661	5666	5671	16.2
0.30	5681	5686	5691	18.3
0.21	5701	5706	5711	20.5
0.13	5721	5726	5731	22.7
0.06	5741	5746	5751	24.5

3.1 HYDRODYNAMIC FORCES

Total hydrodynamic forces were extracted for the waste contact surface using the FSUM command. Using the CONTACT option for the FSUM command sums all contact nodal forces for each time step in the solution. Because the ANSYS model is half-symmetry model, the reactions are doubled to obtain the total force.

3.1.1 Horizontal Excitation

The peak horizontal reaction force shown predicted by ANSYS that is shown in Figure 3-1 is 2.52 x 10^6 lbf, or 3% greater than the theoretical value of 2.45 x 10^6 lbf (see Appendix B for theoretical solutions). The convective response of the waste was determined by subjecting the tank to a horizontal acceleration at the initial time step and then removing the acceleration and allowing the tank waste to oscillate freely under gravity. Figure 3-2 shows the total horizontal reaction force for the half tank model when subjected to horizontal free oscillation. The reaction force is expressed in kips and corresponds to the half-symmetry ANSYS model, so the reactions are half of what are expected for the complete tank The plot shows a fundamental convective frequency of 0.184 Hz, compared to the theoretically predicted frequency of 0.19 Hz.
The effective damping during free oscillation was quantified by determining the rate of decay of the various responses.

Application of the logarithmic decrement δ to the decay of a selected response implies that for a constant critical damping ratio ξ, the ratio of successive peak responses is constant. For small critical damping ratios, the logarithmic decrement can be approximated as

$$\delta \equiv \ln(\frac{x_1}{x_2}) \approx 2\pi\xi \ .$$

More generally, the number of cycles *n* required to achieve a *R*% reduction in amplitude for a given critical damping ratio ξ is

$$n \approx \frac{1}{2\pi\xi}\ln(\frac{100}{100-R}) \ .$$

The data in Figure 3-2 show that under free oscillation, the hydrodynamic force has decreased approximately 96% in three cycles giving an effective critical damping ratio for the convective mode of approximately 17%.

This high level of damping observed is consistent with the alpha damping value of 0.4 used in the model. Rayleigh damping is defined as

$$\zeta = \alpha / 2\omega + \beta\omega / 2$$

For the frequency associated with 1st convective mode and an alpha value of 0.4, the calculated damping is

$$\zeta = 0.4 / 2\pi(2)(0.194) = 16.4\%$$

This is consistent with the high damping level shown for the free oscillation.

Figure 3-1. Horizontal Reaction Force from the ANSYS Rigid Tank Model at 424 in. Waste Level Under Horizontal Seismic Input.

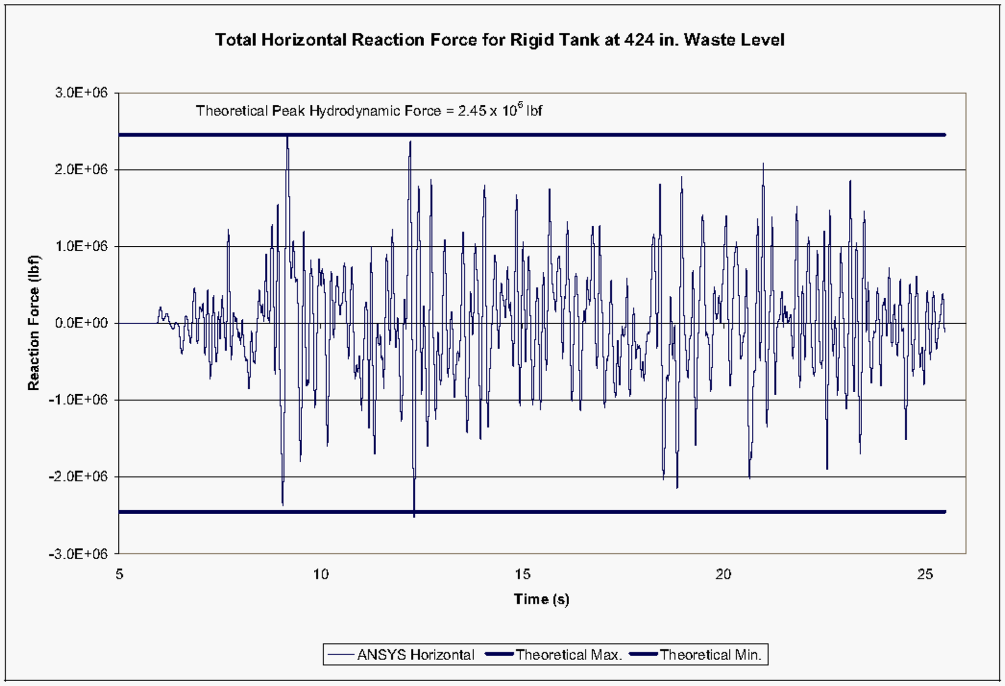
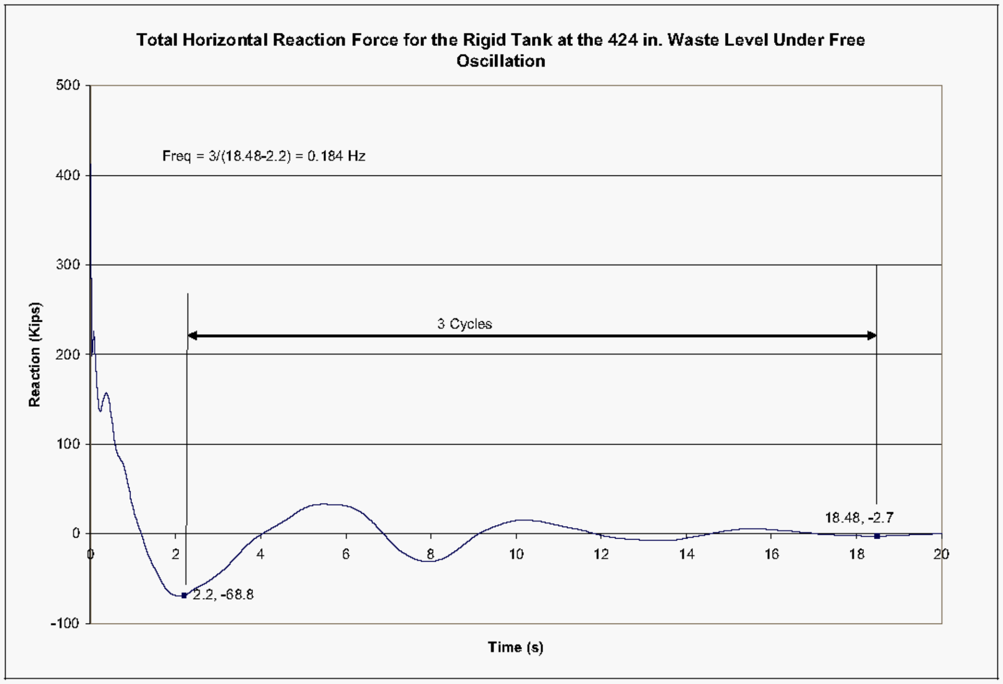


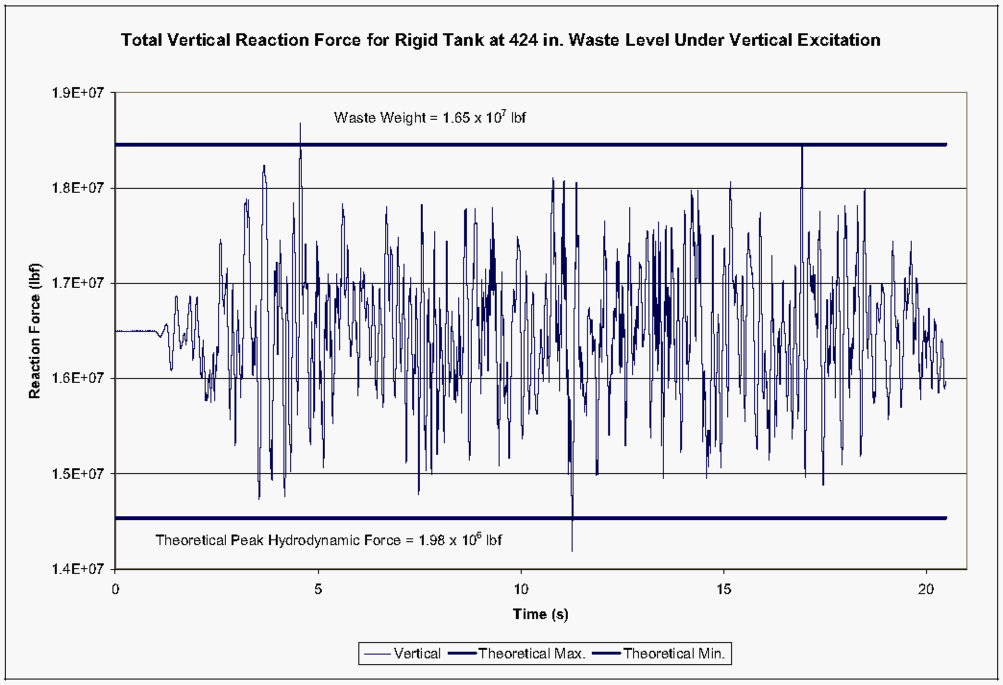
Figure 3-2. Total Horizontal Reaction Force for Rigid Tank Half Model at 424 in. Waste Level Under Free Oscillation – Convective Frequency Response.



3.1.2 Vertical Excitation

Under vertical seismic excitation, the peak vertical hydrodynamic force for a rigid tank is simply the product of the waste mass and the peak acceleration. Given the waste mass of 4.27 x 10^4 lbf-s^2/in, and the vertical zero period acceleration of 0.12*g*, the peak vertical hydrodynamic base force is 1.98 x 10^6 lbf. The peak dynamic component of total vertical reaction force shown in Figure 3-3 is 2.31 x 10^6 lbf, or 17% greater than predicted by theory. The total vertical reaction force is the sum (or difference) of the waste weight and the dynamic component of the reaction force.

Figure 3-3. Vertical Reaction Force for Rigid Tank at 424 in. Waste Level Under Vertical Excitation.



3.2 WASTE PRESSURES

3.2.1 Horizontal Excitation

The hydrodynamic pressures in the tank are caused by impulsive and convective components and depend on the location of the fluid element within the tank. In the case of horizontal excitation, both the impulsive and convective components vary in the circumferential direction as cosine of the angle θ, with the maximum values occurring at θ=0 measured from the plane of excitation, and decreasing to zero hydrodynamic pressure at θ=90° to the plane of excitation. The impulsive hydrodynamic pressure increases with depth, while the convective dynamic pressure is a maximum at the top of the waste. The theoretical peak hydrodynamic pressures are given by Equation 4.24 of BNL 1995. The total pressures are the sum of the hydrostatic pressures and the hydrodynamic pressures. The hydrostatic, peak hydrodynamic and peak total pressures for the elements located on the plane of excitation and 45° from the plane of excitation are shown in Table 3-2 and Table 3-3. The maximum theoretical pressures for the elements located 90° from the plane of excitation are simply the hydrostatic pressures shown in Table 3-1 because the theoretical hydrodynamic pressures are zero at θ=90°.

Table 3-2. Theoretical Maximum Waste Pressures for Horizontal Excitation in the Rigid Tank at 424 in Waste Level for Elements at θ=0.

Normalized Height from Tank Bottom (z/H_l)	Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Pressure (psi gage)	Peak Total Pressure (psi gage)
0.95	5521	1.4	1.8	3.2
0.85	5541	3.8	2.5	6.3
0.77	5561	5.9	3.1	9.0
0.69	5581	8.1	3.7	11.8
0.60	5601	10.3	4.1	14.4
0.52	5621	12.4	4.5	16.9
0.45	5641	14.3	4.8	19.1
0.38	5661	16.2	5.0	21.2
0.30	5681	18.3	5.2	23.5
0.21	5701	20.5	5.3	25.8
0.13	5721	22.7	5.4	28.1
0.06	5741	24.5	5.5	30.0

Table 3-3. Theoretical Maximum Waste Pressures for Horizontal Excitation in the Rigid Tank at 424 in Waste Level for Elements at θ=45°.

Normalized Height from Tank Bottom (z/H_l)	Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Pressure (psi gage)	Peak Total Pressure (psi gage)
0.95	5526	1.4	1.3	2.7
0.85	5546	3.8	1.8	5.6
0.77	5566	5.9	2.2	8.1
0.69	5586	8.1	2.6	10.7
0.60	5606	10.3	2.9	13.2
0.53	5626	12.4	3.2	15.6
0.45	5646	14.3	3.4	17.7
0.38	5666	16.2	3.5	19.7
0.30	5686	18.3	3.7	22.0
0.21	5706	20.5	3.8	24.3
0.13	5726	22.7	3.8	26.5
0.06	5746	24.5	3.9	28.4

The pressure time histories for the waste element sets at θ=0, 45, and 90°, are shown in Figure 3-4, Figure 3-5, and Figure 3-6, with the pressures shown as gage pressure.

Figure 3-4. Waste Pressure Time Histories for the Rigid Tank With 424 in. of Waste Under Horizontal Excitation at θ=0.

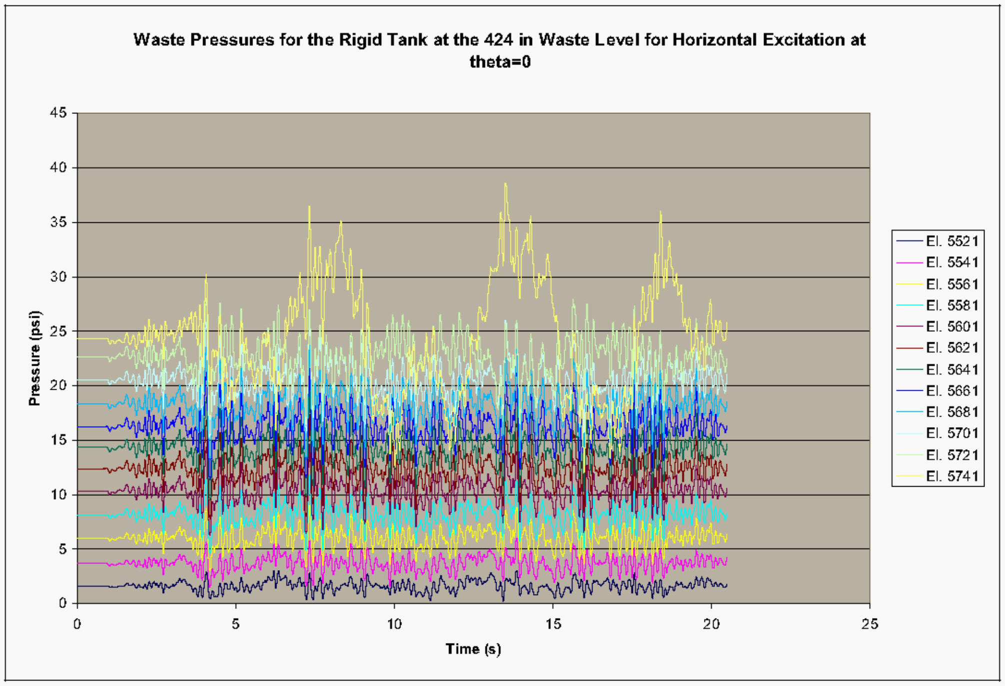


Figure 3-5. Waste Pressure Time Histories for the Rigid Tank With 424 in. of Waste Under Horizontal Excitation at θ=45°.

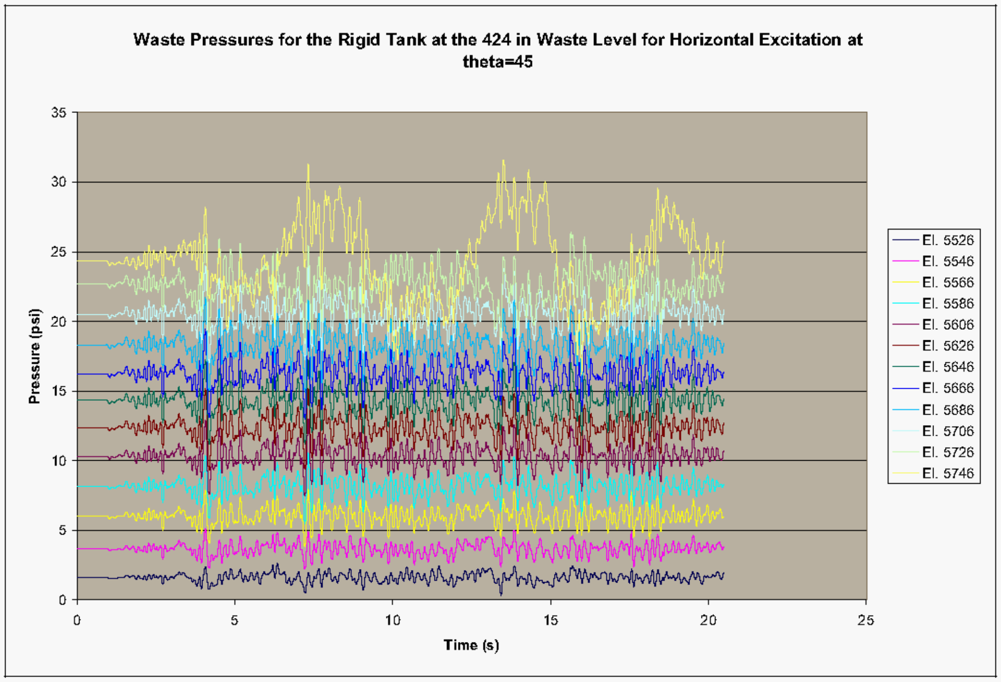
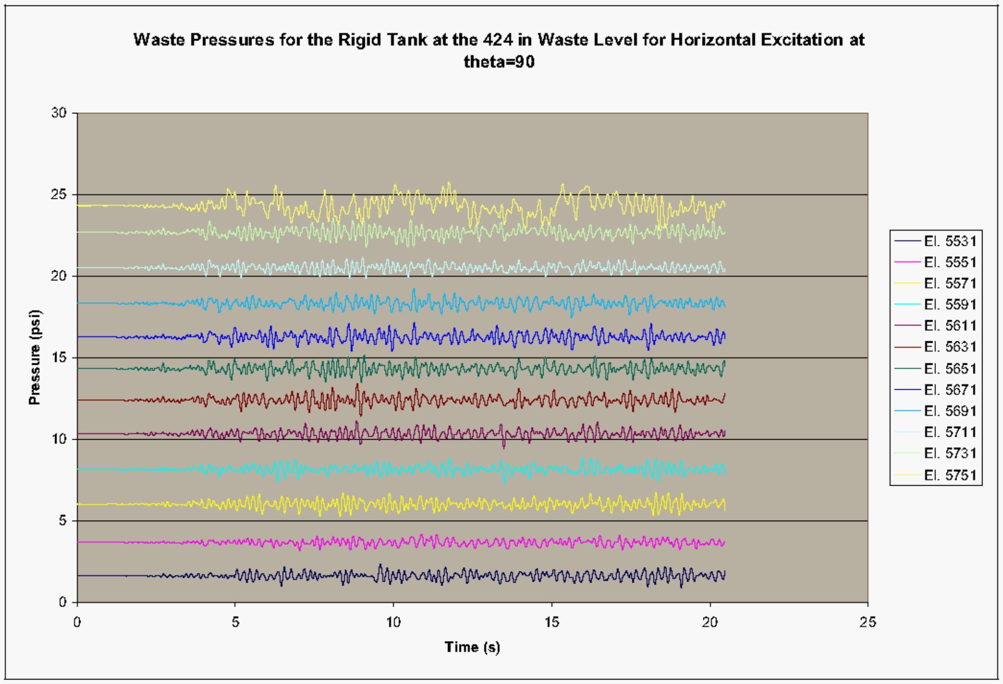


Figure 3-6. Waste Pressure Time Histories for the Rigid Tank With 424 in. of Waste Under Horizontal Excitation at θ=90°.



Another way of presenting some of the information in the previous plots is to look at maximum and minimum pressures as a function of angular position and waste depth. Plots of the actual (that is, as predicted by ANSYS) and theoretical maximum and minimum waste pressures at θ=0, 45, and 90° are shown in Figure 3-7, Figure 3-8, and Figure 3-9, respectively. The time history plots together with the maximum and minimum pressure plots show that the pressures calculated by ANSYS are in good agreement with theoretical predictions except for the lower waste elements at 0 and 45° from the plane of excitation. The time history plots show an unexpected low frequency response near the bottom of the tank that leads to the deviations from theoretical predictions seen in Figure 3-7 and Figure 3-8.

Figure 3-7. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of Rigid Tank at 424 in. Waste Level and θ=0.

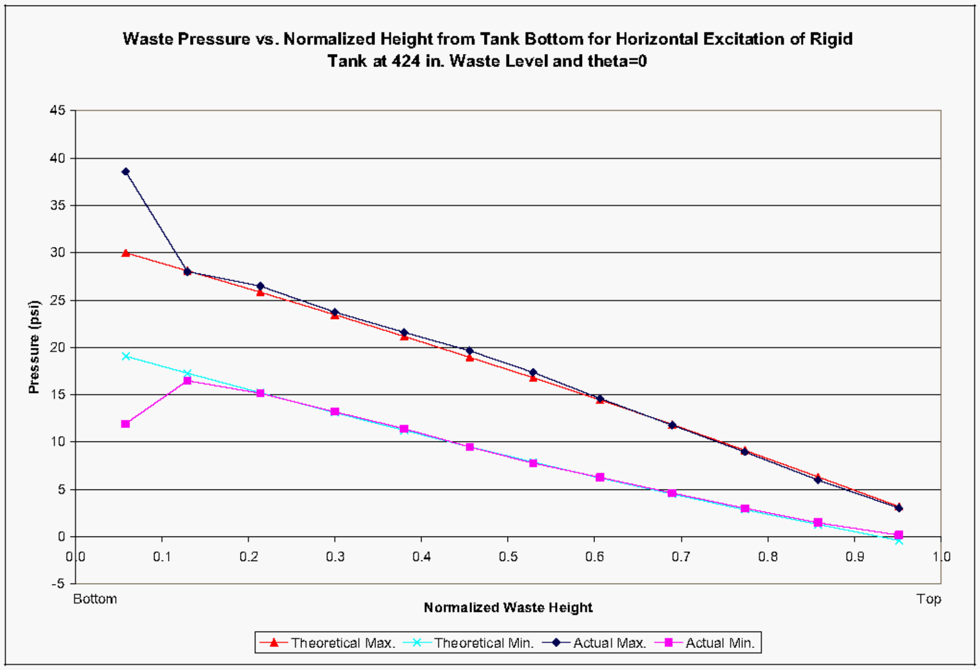


Figure 3-8. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of Rigid Tank at 424 in. Waste Level and θ=45°.

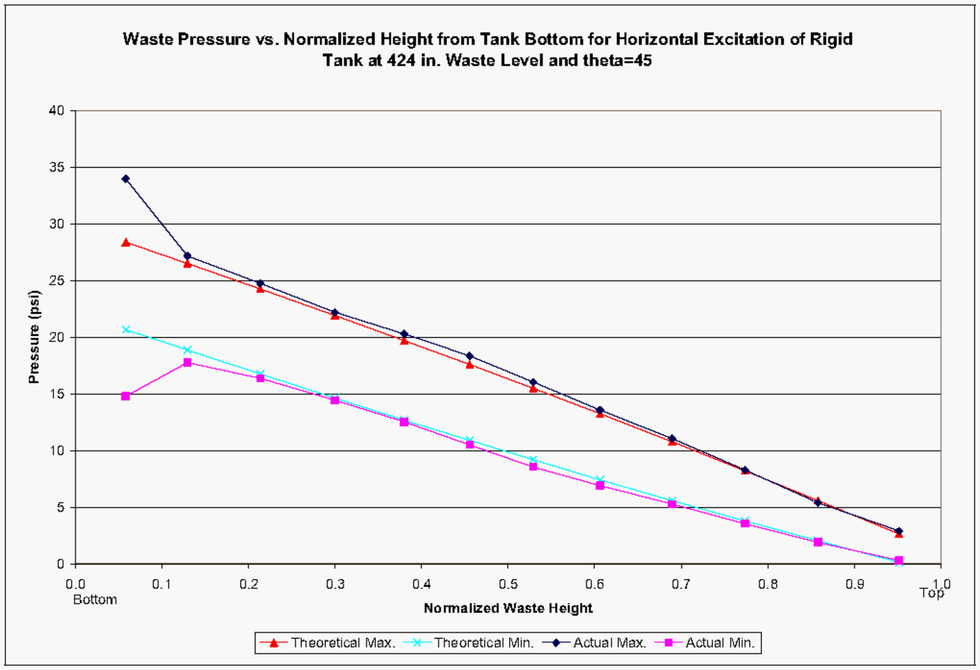
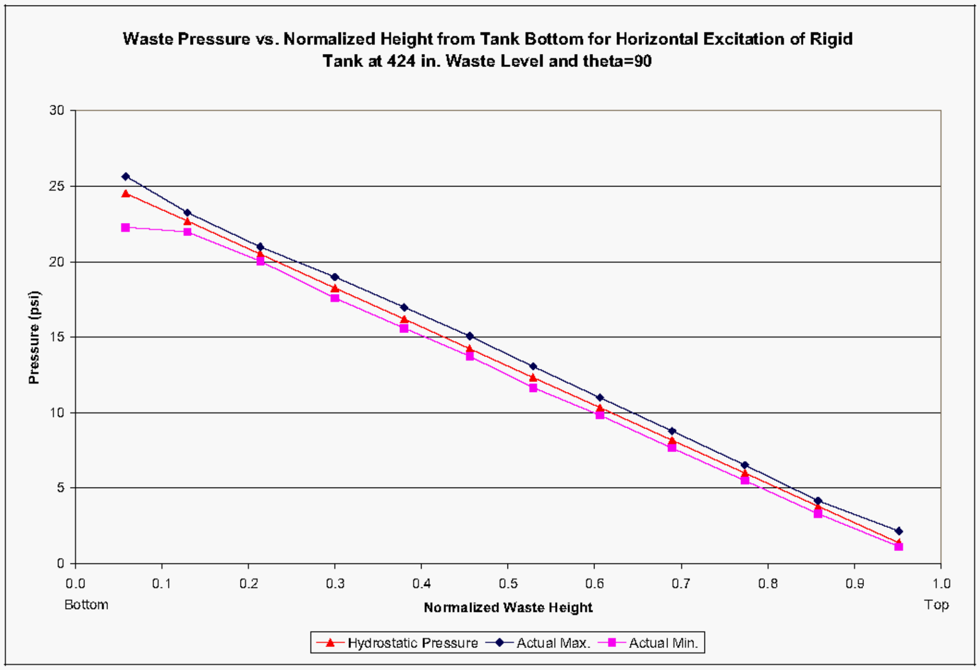


Figure 3-9. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of Rigid Tank at 424 in. Waste Level and θ=90°.



3.2.2 Vertical Excitation

The maximum hydrodynamic pressures induced by the waste on the tank wall due to vertical excitation depend on the vertical location in the waste and are given by Equation 4.55 of BNL 1995. The maximum hydrodynamic and total pressures for the elements at θ=0, 45, and 90° are shown in Table 3-4.

Table 3-4. Theoretical Maximum Wall Pressures for Vertical Excitation in the Rigid Tank at 424 in Waste Level.

Normalized Height from Tank Bottom (z/H_l)	Θ=0° Element No.	Θ=45° Element No.	Θ=90° Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Wall Pressure (psi gage)	Peak Total Pressure (psi gage)
0.95	5521	5526	5531	1.4	0.2	1.6
0.85	5541	5546	5551	3.8	0.6	4.4
0.77	5561	5566	5571	5.9	0.9	6.8
0.69	5581	5586	5591	8.1	1.2	9.3
0.60	5601	5606	5611	10.3	1.5	11.8
0.53	5621	5626	5631	12.4	1.7	14.1
0.45	5641	5646	5651	14.3	1.9	16.2
0.38	5661	5666	5671	16.2	2.1	18.3
0.30	5681	5686	5691	18.3	2.2	20.5
0.21	5701	5706	5711	20.5	2.4	22.9
0.13	5721	5726	5731	22.7	2.5	25.2
0.06	5741	5746	5751	24.5	2.5	27.0

Plots of waste pressure time histories for elements at the 0, 45, and 90° locations are shown in Figure 3-10, Figure 3-11, and Figure 3-12, respectively. The plots show excellent agreement with theory and the response at the three locations is essentially the same, as expected.

Figure 3-10. Waste Pressure Time Histories for the Rigid Tank With 424 in. of Waste Under Vertical Excitation at θ=0.

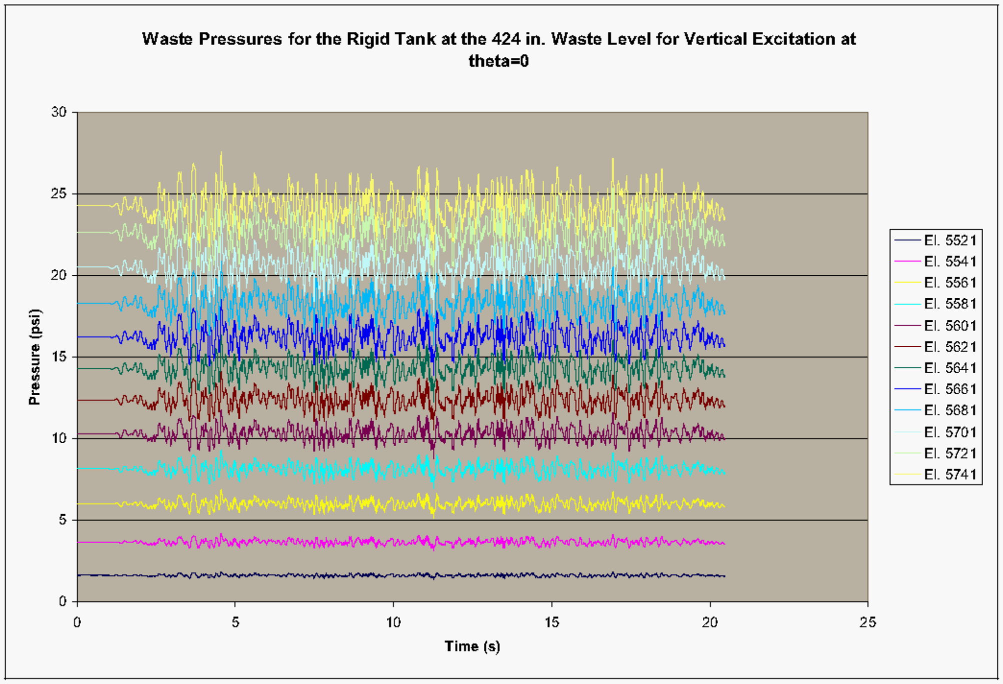


Figure 3-11. Waste Pressure Time Histories for the Rigid Tank With 424 in. of Waste Under Vertical Excitation at θ=45°.

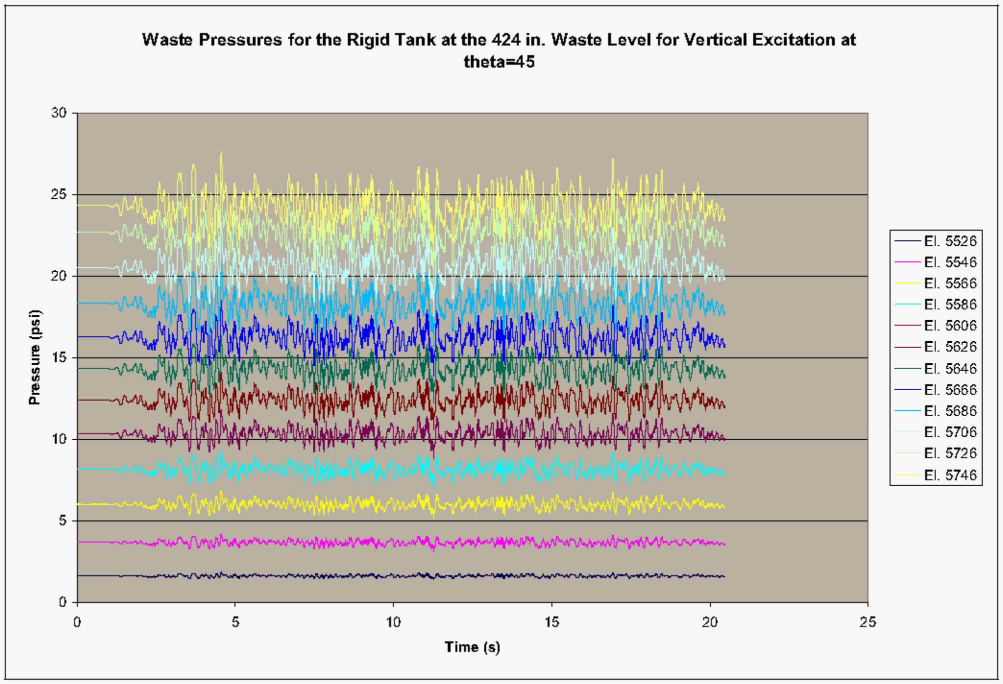
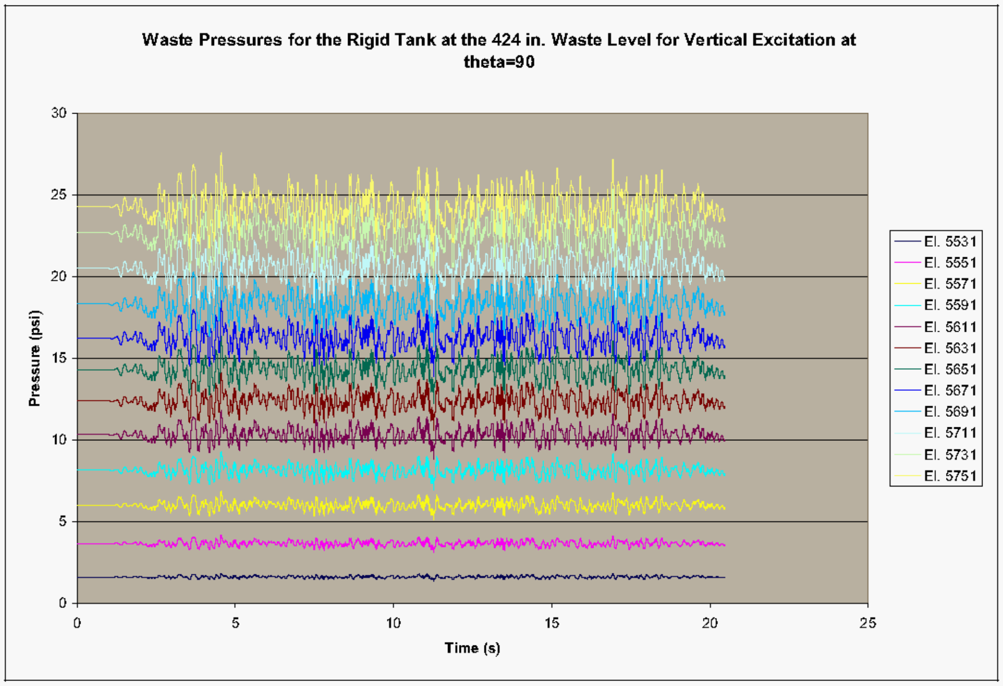
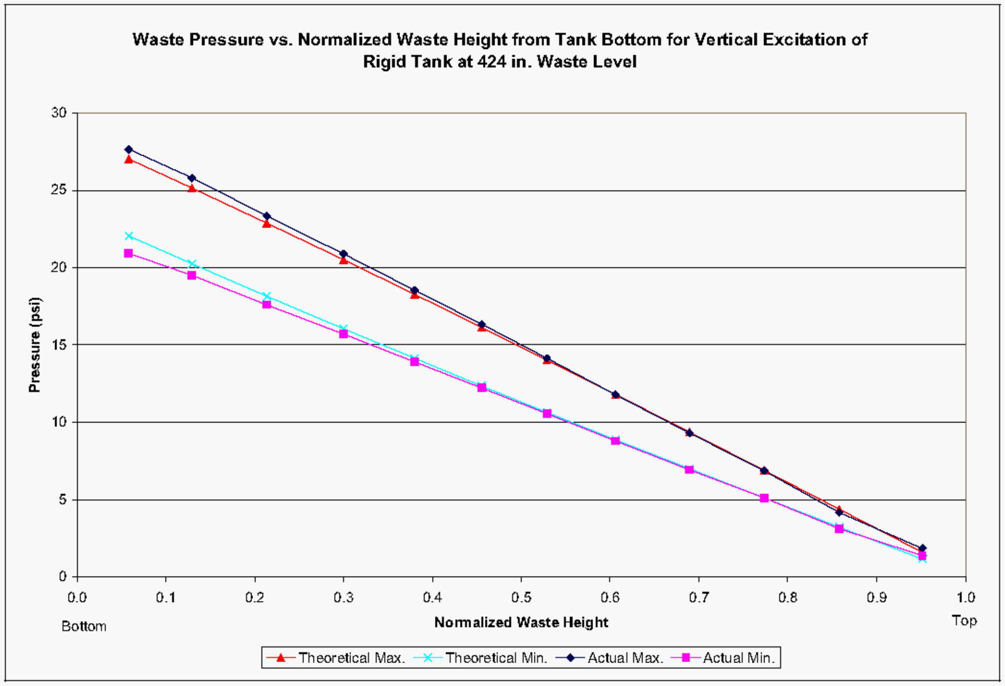


Figure 3-12. Waste Pressure Time Histories for the Rigid Tank With 424 in. of Waste Under Vertical Excitation at θ=90°.



The actual (that is, as predicted by ANSYS) maximum and minimum pressures independent of the angle θ from the plane of excitation are shown in Figure 3-13 along with the theoretical maximum and minimum pressures for the elements.

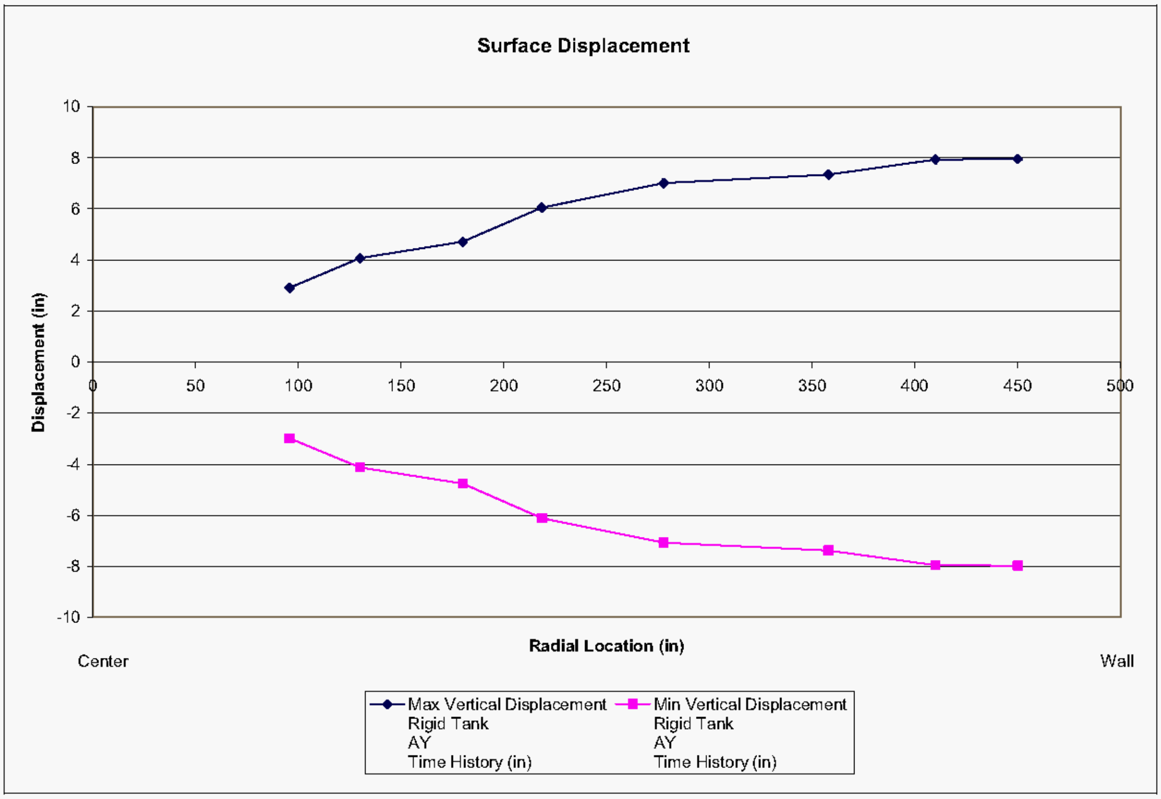
Figure 3-13. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Vertical Excitation of Rigid Tank at 424 in. Waste Level.



3.3 SLOSH HEIGHT RESULTS

The maximum slosh height over all surface waste elements, regardless of time, is shown as Figure 3-14. According to Equation 4.60 of BNL 1995, the maximum predicted slosh height due to horizontal excitation is 23.7 in. The maximum slosh height from the simulation is approximately 8 in., or 1/3 of the open top theoretical value. Clearly, the ability to accurately predict slosh heights and the associated convective response is a limitation of the ANSYS model.

Figure 3-14. Maximum Slosh Height Over All Waste Elements for Horizontal Excitation.



4.0 RIGID TANK MODEL AT 460 INCH WASTE LEVEL

The response of the tank and contained liquid to seismic excitation with the liquid initially at the 460 in. level does not have a closed form analytical solution because of the interaction of the liquid free surface with the curved surface of the tank dome. However, the solutions obtained with ANSYS will be compared to the theoretical solution for the rigid open tank with the hinged top condition and 460 in. waste level.
The ANSYS simulation for vertical seismic excitation was inadvertently run with a waste level of 452 rather than 460 in., and the results presented for vertical input are for the 452 in. waste level. For vertical input, the difference between the two waste levels is minor, and simulations were not re-run at the 460 in. waste level. However, for consistency, the ANSYS results were compared to theoretical results for an open top tank at the 452 in. waste level. Similarly, the free oscillation convective frequency response was performed at the 452 in. waste level.

4.1 HYDRODYNAMIC FORCES

4.1.1 Horizontal Excitation

If the contributions of the impulsive mode and first three convective modes are combined in a square-root-sum-of-squares (SRSS) fashion, the theoretical maximum horizontal hydrodynamic force is 3.0×10^6 lbf, based on a zero-period acceleration for the impulsive response, and convective accelerations from the 0.5% damped spectrum. The total horizontal reaction force time history reported by ANSYS is shown as Figure 4-1. The peak reaction force is 3.29×10^6 lbf, or 10% greater than the open top theoretical value.

The convective response of the waste was determined by subjecting the tank to a horizontal acceleration at the initial time step and then removing the acceleration and allowing the tank waste to oscillate freely under gravity. As shown in Figure 4-2, the fundamental convective frequency is 0.192 Hz, slightly less than the open top theoretical value of 0.2 Hz. The data in Figure 4-2 show that under free oscillation, the hydrodynamic force has decreased approximately 98% in three cycles giving an effective critical damping ratio for the convective mode of approximately 20% at the 460 in. waste level.

Figure 4-1. Total Horizontal Reaction Force for the Rigid Tank Under Horizontal Seismic Excitation at the 460 in. Waste Level.

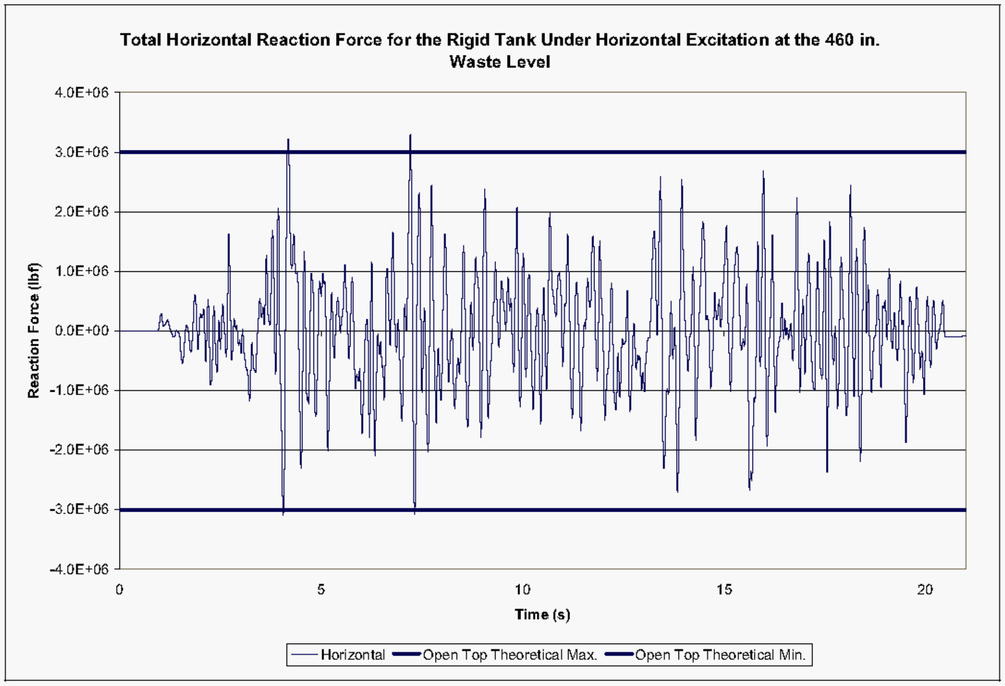
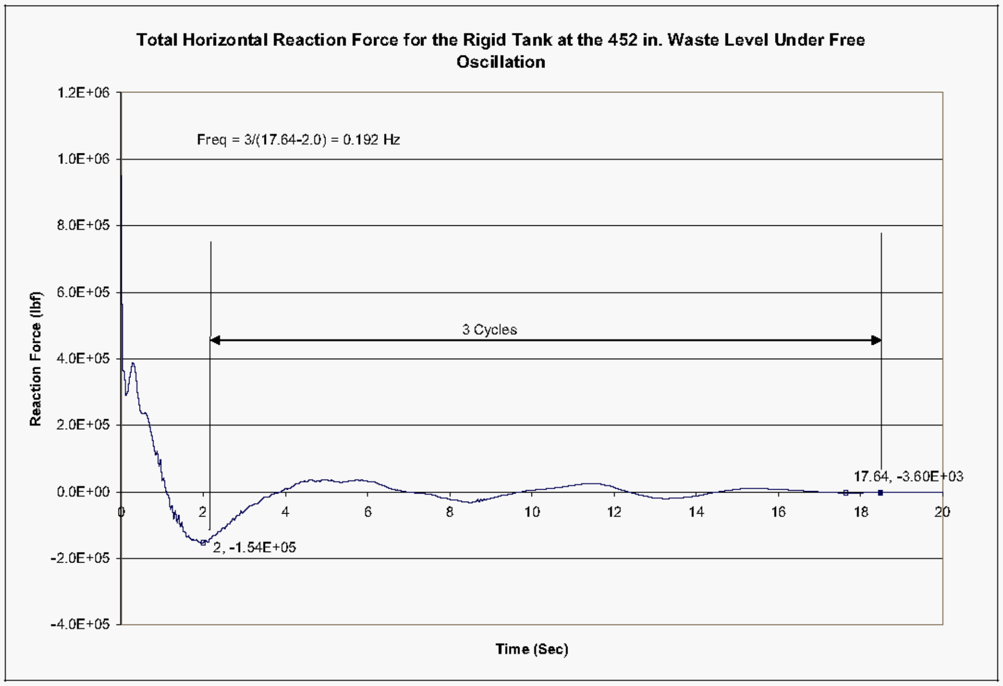


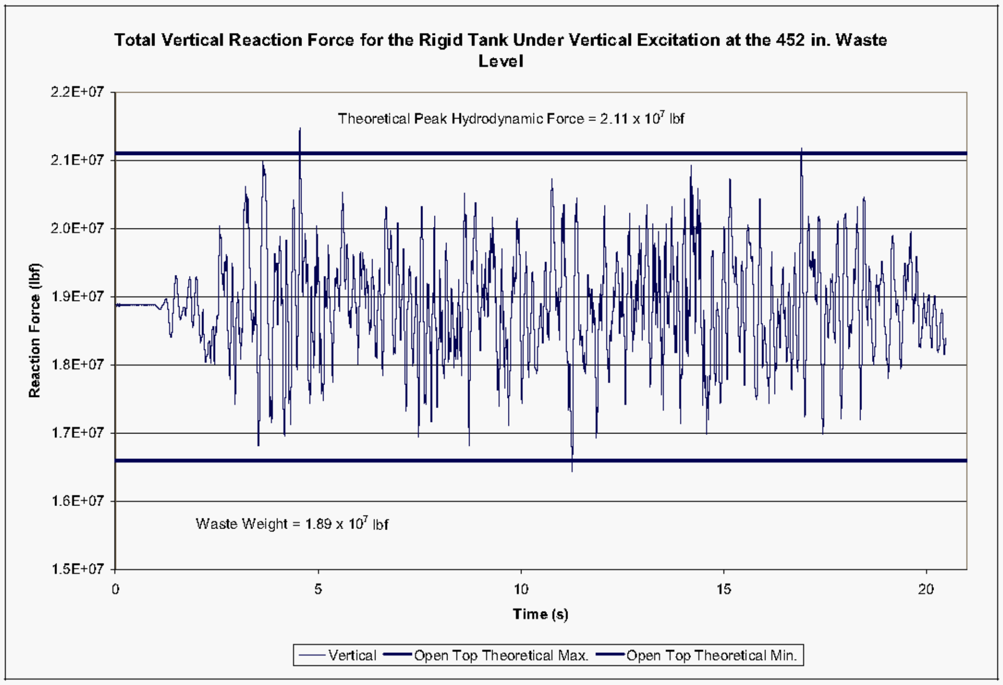
Figure 4-2. Total Horizontal Reaction Force for the Rigid Tank at the 452 in. Waste Level Under Free Oscillation – Convective Response.



4.1.2 Vertical Excitation

Given the waste mass of 4.88 x 10^4 lbf-s^2/in, (for the 452 in. waste level) and the vertical zero period acceleration of 0.12*g*, the dynamic component of the peak theoretical vertical base force is 2.26 x 10^6 lbf, resulting in a theoretical peak total reaction force of 2.11 x 10^7 lbf. The peak total vertical reaction force shown in Figure 4-3 is 2.15 x 10^7 lbf, or 2% greater than the predicted by theory. The peak dynamic component is 2.57 x 10^6 lbf, which is 14% greater than the open top theoretical value.

Figure 4-3. Total Vertical Reaction Force for Rigid Tank at 452 in. Waste Level Under Vertical Seismic Excitation.



4.2 WASTE PRESSURES

4.2.1 Horizontal Excitation

Although no closed form solution exists for the 460 in. waste level, theoretical dynamic pressures were calculated using Equation 4.24 of BNL 1995 *based on an open tank with 460 in. of waste and a hinged top condition*. This solution is presented along with the actual results for comparison purposes.

The hydrostatic, peak hydrodynamic and peak total pressures for the elements at zero, and 45° from the plane of excitation are shown in Table 4-1 and Table 4-2. The maximum theoretical pressures for the elements located 90° from the plane of excitation are simply the hydrostatic pressures shown in the two tables because the theoretical hydrodynamic pressures are zero at θ=90°.

Table 4-1. Theoretical Maximum Absolute Waste Pressures for Horizontal Excitation in the Rigid Open Top Tank at 460 in. Waste Level for Elements at θ=0.

Normalized Height from Tank Bottom (z/H_l)	θ=0 Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Pressure (psi gage)	Peak Total Pressure (psi gage)
0.99	5471	0.3	1.7	2.0
0.95	5511	1.4	2.0	3.4
0.87	5551	3.8	2.7	6.5
0.79	5791	6.5	3.4	9.9
0.71	5811	8.8	4.0	12.8
0.63	5831	11.1	4.5	15.6
0.56	5851	13.5	4.9	18.4
0.48	5871	15.7	5.3	21.0
0.42	5891	17.8	5.5	23.3
0.35	5911	19.8	5.7	25.5
0.28	5931	22.0	5.9	27.9
0.20	5951	24.5	6.0	30.5
0.12	5971	26.8	6.1	32.9
0.05	5991	28.8	6.2	35.0

Table 4-2. Theoretical Maximum Absolute Waste Pressures for Horizontal Excitation in the Rigid Open Top Tank at 460 in. Waste Level for Elements at θ=45°.

Normalized Height from Tank Bottom (z/H_l)	θ=45° Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Pressure (psi gage)	Peak Total Pressure (psi gage)
0.99	5476	0.3	1.2	1.5
0.95	5516	1.4	1.4	2.8
0.87	5556	3.8	1.9	5.7
0.79	5796	6.5	2.4	8.9
0.71	5816	8.8	2.8	11.6
0.63	5836	11.1	3.2	14.3
0.56	5856	13.5	3.5	17.0
0.48	5876	15.7	3.7	19.4
0.42	5896	17.8	3.9	21.7
0.35	5916	19.8	4.0	23.8
0.28	5936	22.0	4.2	26.2
0.20	5956	24.5	4.3	28.8
0.12	5976	26.8	4.3	31.1
0.05	5996	28.8	4.4	33.2

The pressure time histories for waste element sets at θ=0, 45, and 90°, are shown in Figure 4-4 through Figure 4-8. Comparisons of the maximum and minimum pressures expected for an open top tank to the maximum and minimum pressures obtained from the computer simulations are shown in Figure 4-9, Figure 4-10, and Figure 4-11. Excursions from the open top solution are evident in Figure 4-9 and Figure 4-10. In both plots, the biggest differences occur near the waste free surface, and near the bottom of the tank.

The pressure time histories for element 5471 at the top of the waste and element 5991 at the bottom of the waste shown in Figure 4-5 indicate that the deviations from theory are not at singular isolated points, but rather are indicative of the general behavior of the solution. Similar remarks apply to elements 5476 and 5996 shown in Figure 4-7.

Figure 4-4. Waste Pressure Time Histories for the Rigid Tank With 460 in. of Waste Under Horizontal Excitation at θ=0.

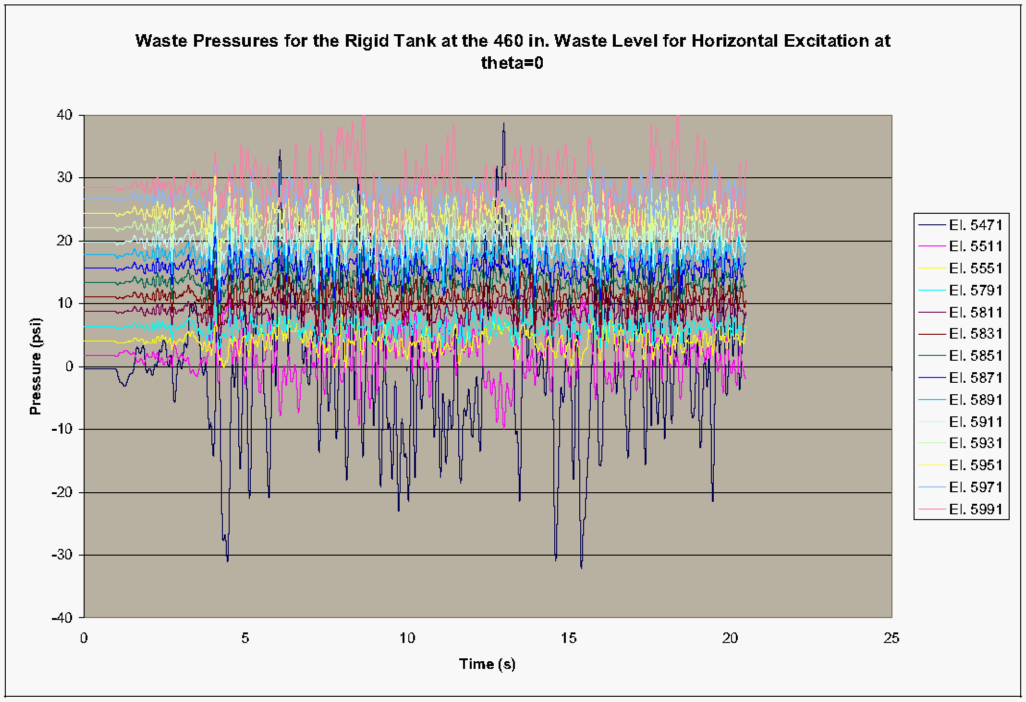


Figure 4-5. Selected Waste Pressure Time Histories for the Rigid Tank With 460 in. of Waste Under Horizontal Excitation at θ=0.

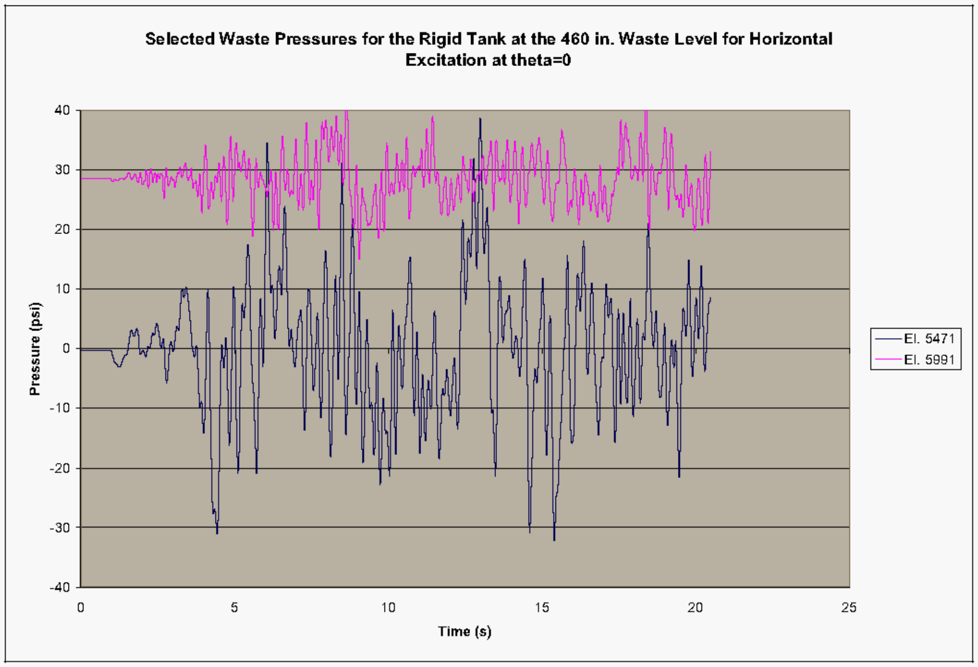


Figure 4-6. Waste Pressure Time Histories for the Rigid Tank With 460 in. of Waste Under Horizontal Excitation at θ=45°.

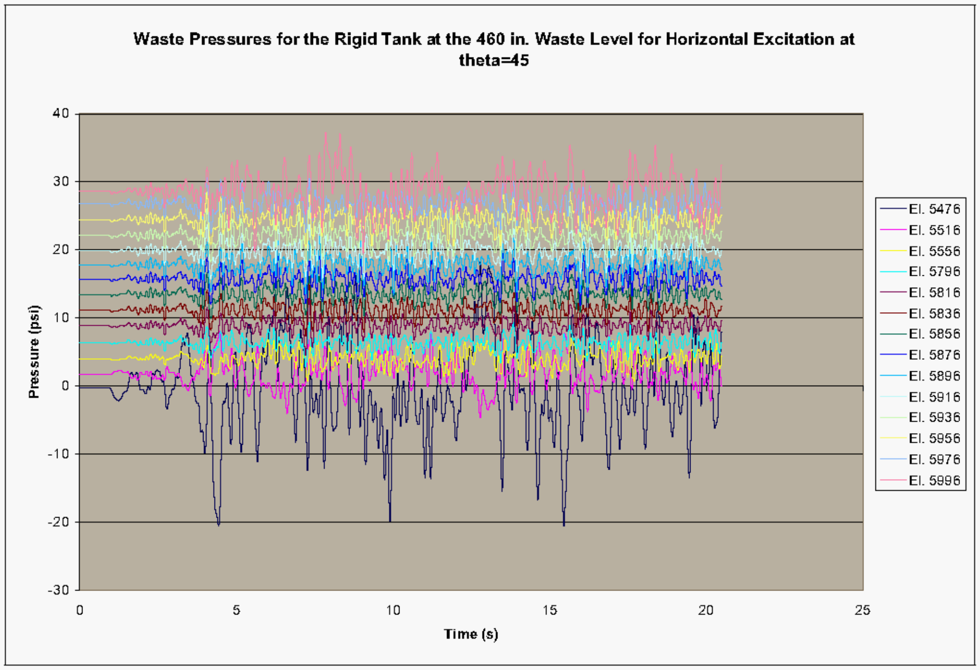


Figure 4-7. Selected Waste Pressure Time Histories for the Rigid Tank With 460 in. of Waste Under Horizontal Excitation at θ=45°.

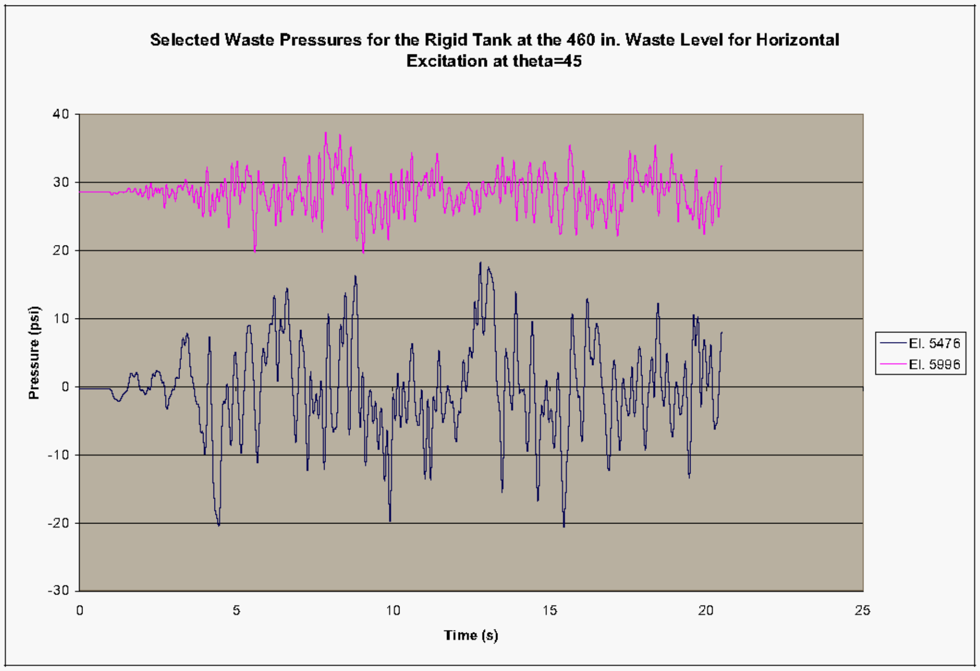


Figure 4-8. Waste Pressure Time Histories for the Rigid Tank With 460 in. of Waste Under Horizontal Excitation at θ=90°.

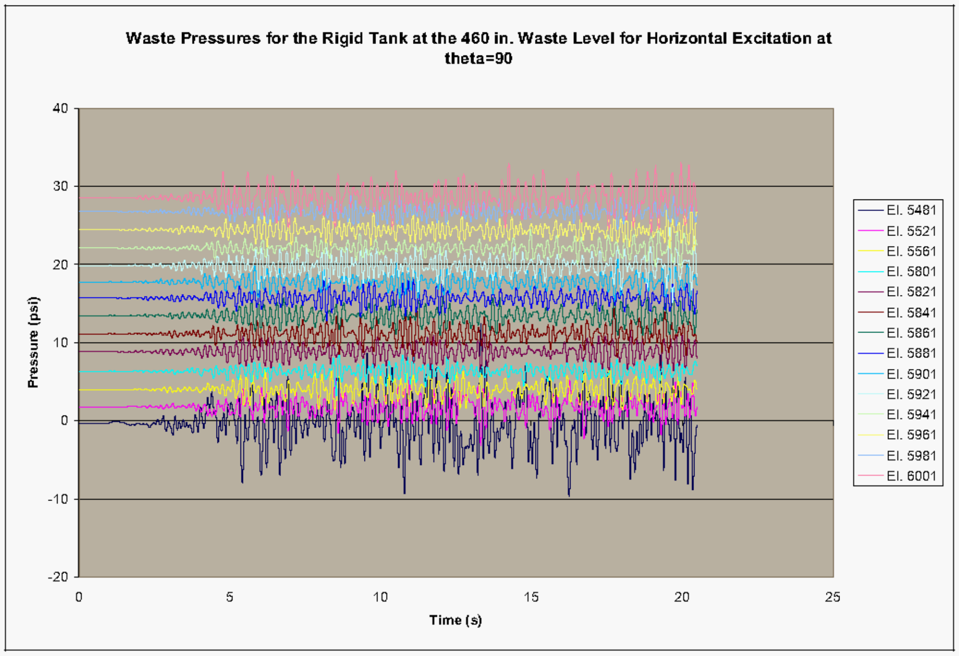


Figure 4-9. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of Rigid Tank at 460 in. Waste Level and θ=0.

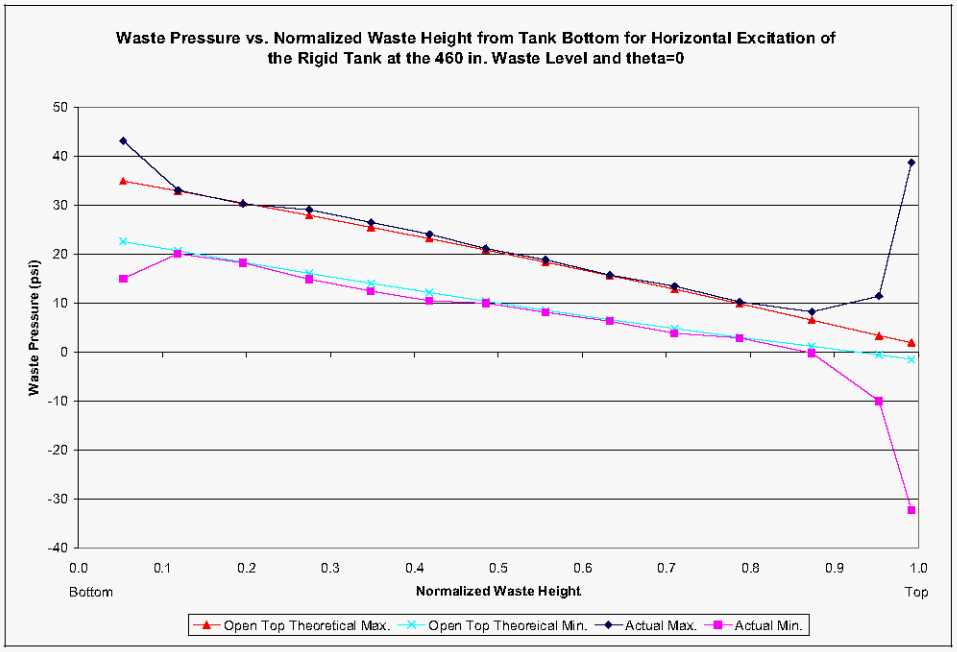


Figure 4-10. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of Rigid Tank at 460 in. Waste Level and θ=45°.

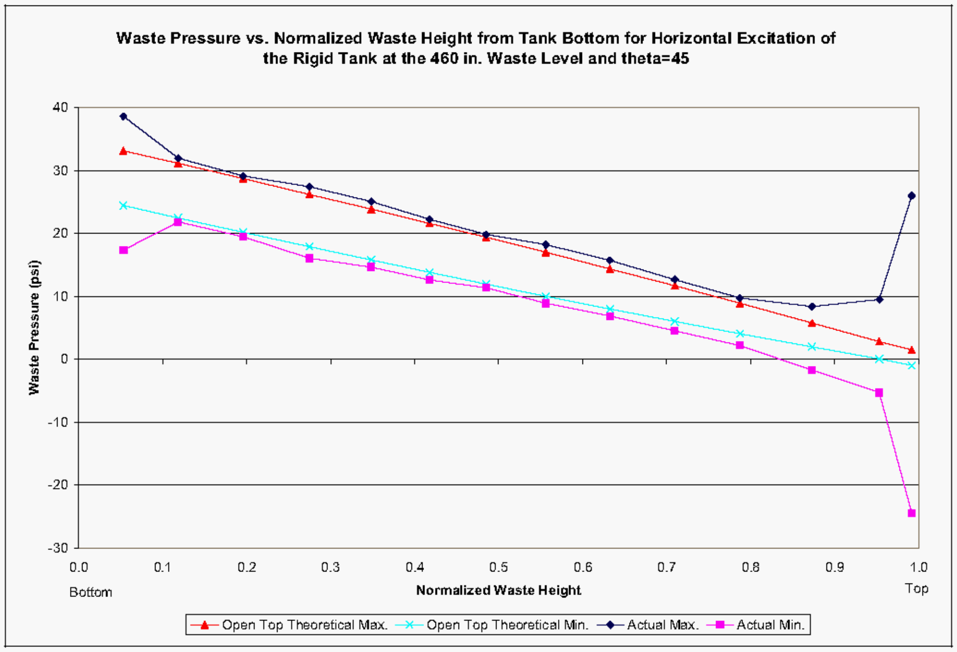
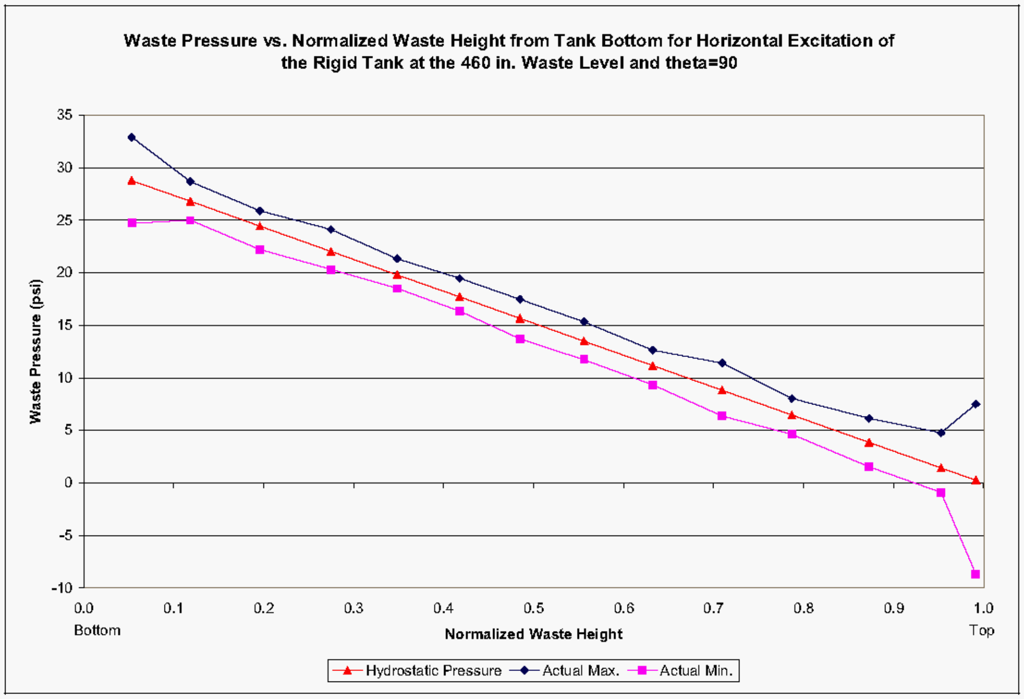


Figure 4-11. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of Rigid Tank at 460 in. Waste Level and θ=90°.



4.2.2 Vertical Excitation

Expected pressures for vertical excitation of the rigid tank at the 452 in. waste level are shown in Table 4-3.

Table 4-3. Theoretical Maximum Wall Pressures for Vertical Excitation of an Open Top Rigid Tank at the 452 in. Waste Level.

Normalized Height from Tank Bottom (z/H_l)	θ=0 Element No.	θ=45° Element No.	θ=90° Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Wall Pressure (psi gage)	Peak Total Pressure (psi gage)
0.97	6321	6326	6331	0.9	0.1	3.0
0.89	6341	6346	6351	3.3	0.5	3.8
0.80	5731	5736	5741	5.9	0.9	6.8
0.72	5751	5756	5761	8.2	1.2	9.4
0.65	5771	5776	5781	10.6	1.5	12.1
0.57	5791	5796	5801	13.0	1.8	14.8
0.49	5811	5816	5821	15.2	2.1	17.3
0.42	5831	5836	5841	17.2	2.3	19.5
0.35	5851	5856	5861	19.3	2.4	21.7
0.28	5871	5876	5881	21.5	2.6	24.1
0.20	5891	5896	5901	23.9	2.7	26.6
0.12	5911	5916	5921	26.3	2.8	29.1
0.05	5931	5936	5941	28.3	2.9	31.2

Waste element pressure time histories for vertical excitation are shown in Figure 4-12 through Figure 4-15. Comparison of maximum and minimum pressures from the simulation and the open top solution is presented as Figure 4-16. The agreement between the simulation and the open top theory is good, but shows some deviations at elements near the free surface. The details for the θ=0 case are shown in Figure 4-13. For the waste contact elements in this model, the contact stiffness of the top two layers (between 381 and 452 in) were softened relative to the rest of the waste to minimize the high contact pressures. This was done to minimize the high contact pressures that were occurring at the haunch of the primary tank. With respect to the rigid tank, the resulting contact stiffness was too soft, allowing for significant contact penetration to occur (0.20 in), resulting in the variation in the waste pressures shown in Figure 4-13. Softening of contact element stiffness was not necessary in the flexible tank models due to the additional compliance of the primary tank.

The pressure time history for a waste element at the bottom central portion of the tank (element 5971) is shown as Figure 4-17. The theoretical hydrostatic pressure for element 5971 is 29.87 lbf/in^2, and the theoretical peak hydrodynamic pressure is 3.58 lbf/in^2. That is, the predicted minimum and maximum pressures at this location are 33.45, and 26.29 lbf/in^2, respectively. The actual maximum and minimum values as shown in Figure 4-17 are 34.05 and 26.09 lbf/in^2, respectively.

Figure 4-12. Waste Pressure Time Histories for the Rigid Tank With 452 in. of Waste Under Vertical Excitation at θ=0.

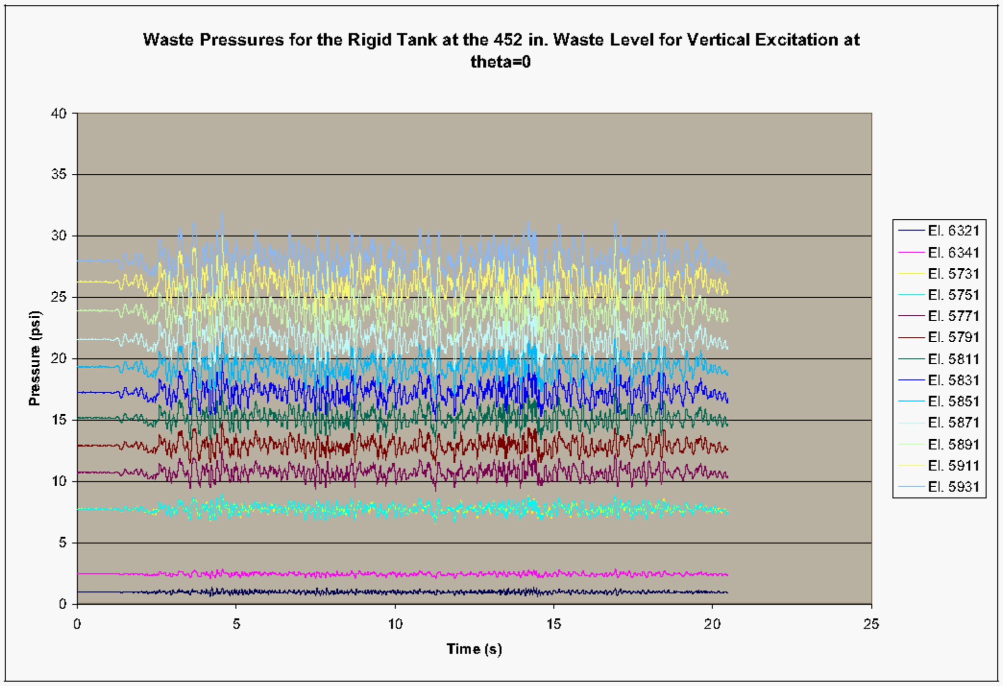


Figure 4-13. Selected Waste Pressure Time Histories for the Rigid Tank With 452 in. of Waste Under Vertical Excitation at θ=0.

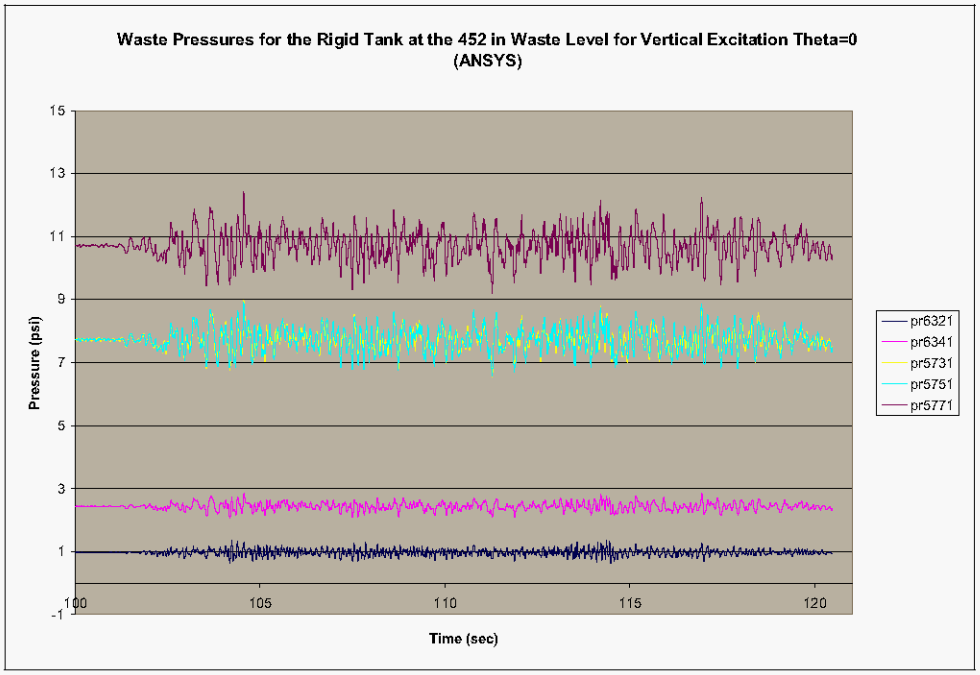


Figure 4-14. Waste Pressure Time Histories for the Rigid Tank With 452 in. of Waste Under Vertical Excitation at θ=45°.

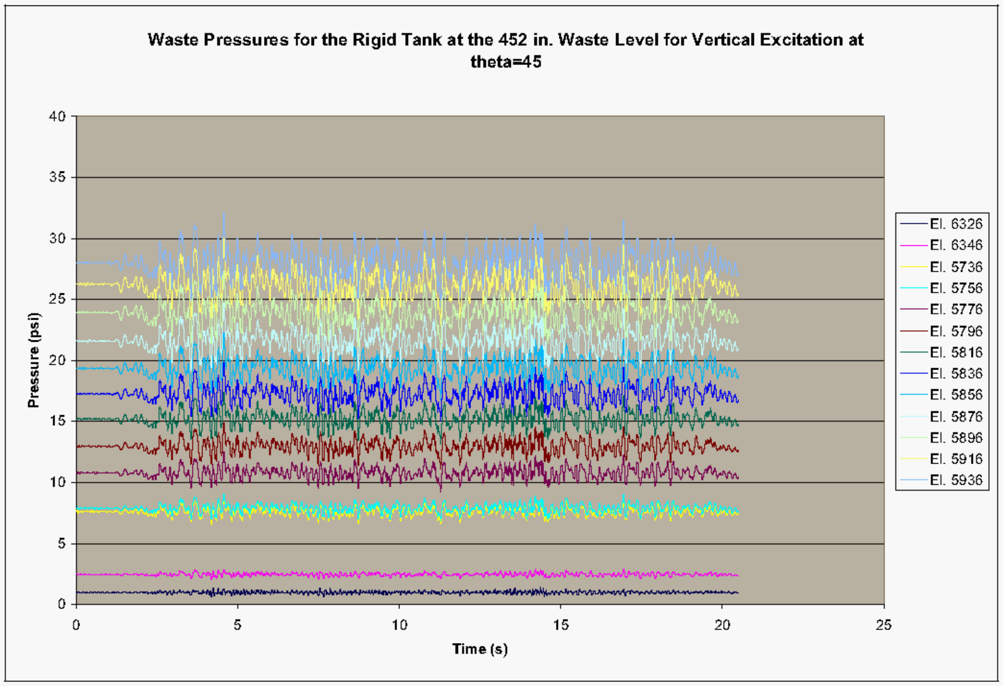


Figure 4-15. Waste Pressure Time Histories for the Rigid Tank With 452 in. of Waste Under Vertical Excitation at θ=90°.

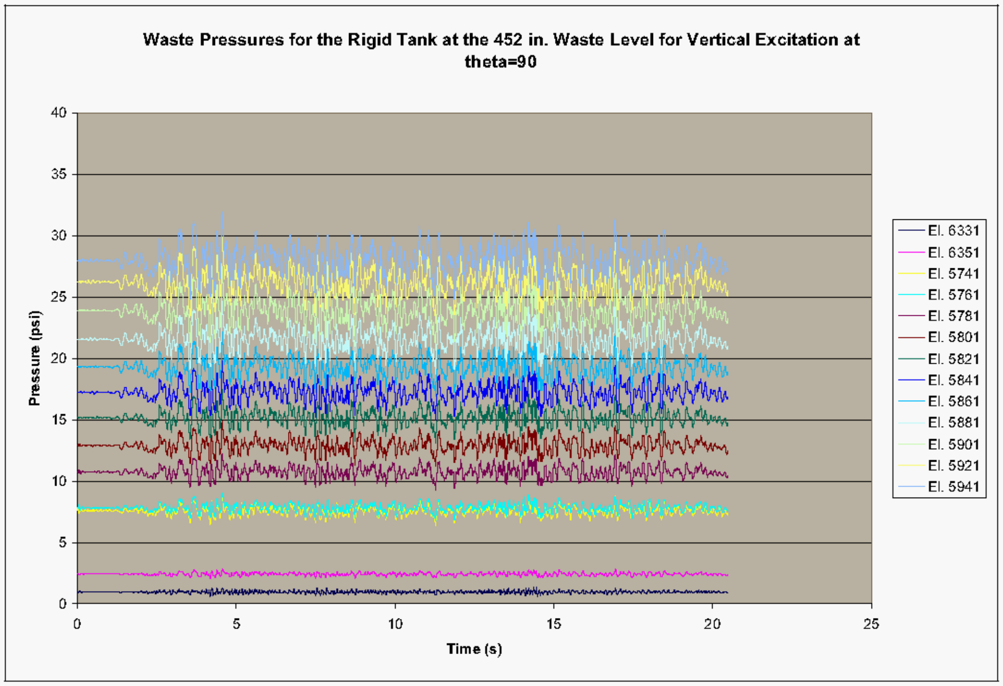


Figure 4-16. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Vertical Excitation of Rigid Tank at 452 in. Waste Level.

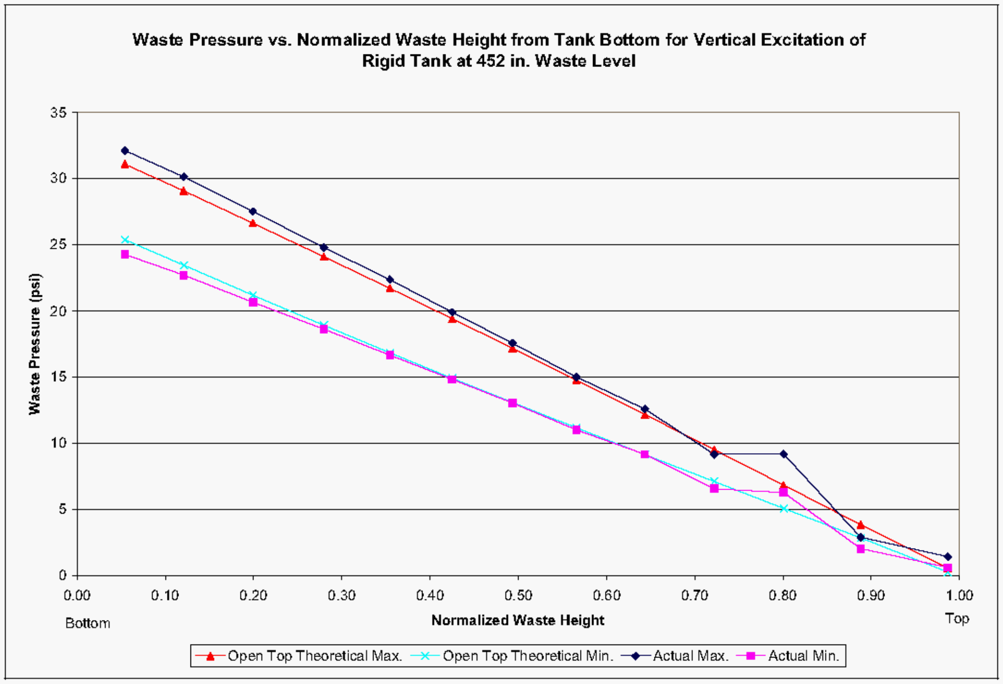
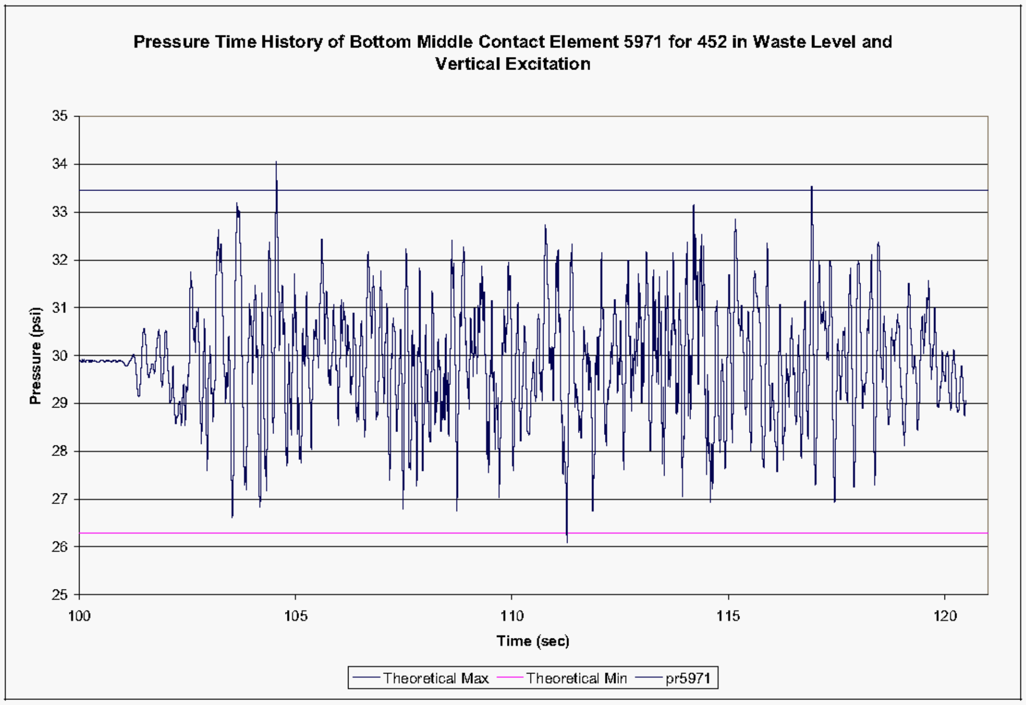


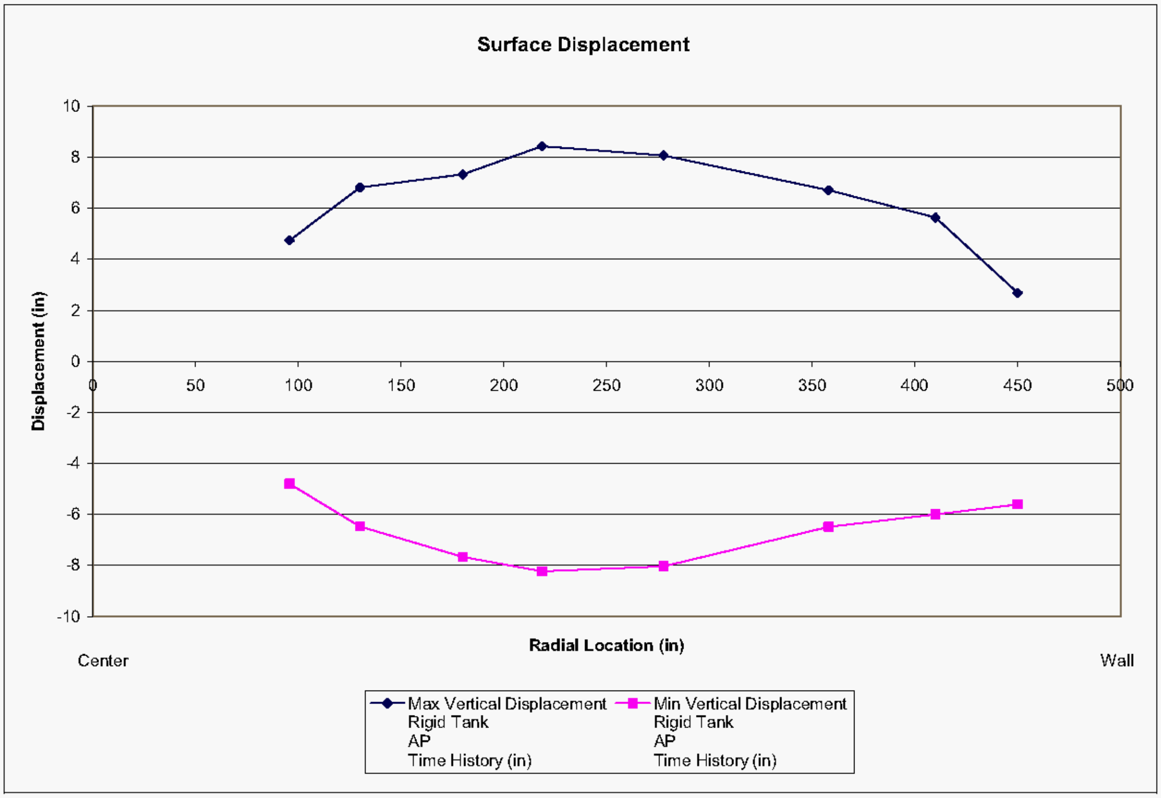
Figure 4-17. Waste Pressure Time History for the Bottom Center Waste Element 5971 for the Rigid Tank at the 452 in Waste Level and Vertical Excitation



4.3 SLOSH HEIGHT RESULTS

The maximum slosh height over all surface waste elements, regardless of time, is shown as Figure 4-18. The maximum slosh height according to the theory for the open top tank is 24.5 in. while the maximum slosh height from the simulation is approximately 8 in., or 1/3 of the open top theoretical value. Clearly, the ability to accurately predict slosh heights and the associated convective response is a limitation of the ANSYS model.

Figure 4-18. Maximum Slosh Height Time Over All Waste Elements for Horizontal Excitation of the Rigid Tank at the 460 in. Waste Level.



5.0 FLEXIBLE TANK ANSYS MODEL AT 424 INCH WASTE LEVEL

5.1 HYDRODYNAMIC FORCES

5.1.1 Horizontal Excitation

The peak horizontal hydrodynamic forces for the flexible tank are again calculated via Equation 4.31 of BNL 1995 with the instantaneous accelerations replaced by the appropriate spectral accelerations. If the contributions of the impulsive mode and first three convective modes are combined in a square-root-sum-of-squares (SRSS) fashion, the theoretical maximum horizontal hydrodynamic force is 7.65 x 10^6 lbf. The above value is based on spectral accelerations from the 4% damped spectrum.

The peak horizontal reaction force calculated by ANSYS that is shown in Figure 5-1 is 8.67 x 10^6 lbf, or 13% greater than the theoretical value. As before, the convective response of the waste was determined by subjecting the rigid tank to a horizontal acceleration at the initial time step and then removing the acceleration and allowing the tank waste to oscillate freely under gravity. Figure 5-2 shows the total horizontal reaction force for the ANSYS half tank model when subjected to horizontal free oscillation. The convective reaction was determined from free oscillation of the rigid tank, so Figure 5-2 is a duplicate of Figure 3-2 and is shown in this section for the convenience of the reader. As in Figure 3-2, the reaction force is expressed in kips and corresponds to the half-symmetry ANSYS model, so the reactions are half of what are expected for the complete tank The plot shows a fundamental convective frequency of 0.184 Hz, compared to the theoretically predicted frequency of 0.19 Hz.

The impulsive frequency response is shown in Figure 5-3. The impulsive frequency was calculated by subtracting the reaction force for the rigid tank from the reaction force for the flexible tank. Because the reaction force for the rigid tank represents the convective reaction, and the reaction force for the flexible tank is the sum and impulsive and convective components, the difference between the total reaction for the flexible tank and the total (convective) reaction for the rigid tank isolates the impulsive frequency for the flexible tank. The impulsive frequency calculated in this manner is 7.5 Hz compared to a theoretical value of 7 Hz.

Figure 5-1. Horizontal Reaction Force for the Flexible Tank ANSYS Model Under Horizontal Seismic Input at the 424 in. Waste Level.

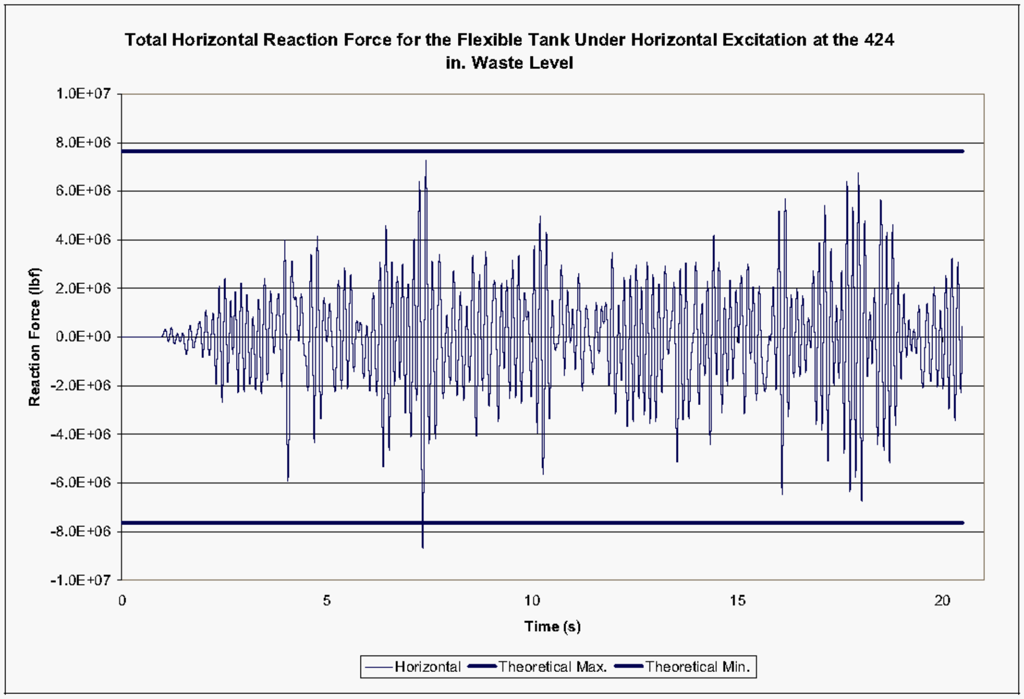


Figure 5-2. Total Horizontal Reaction Force for Rigid Tank at the 424 in. Waste Level Under Free Oscillation – Convective Frequency Response.

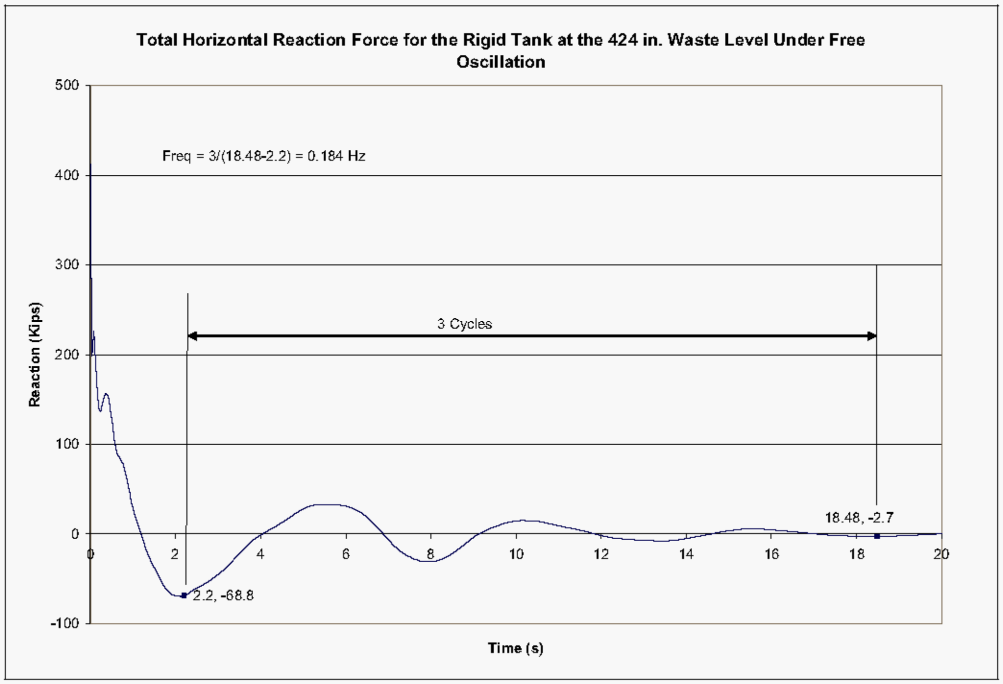
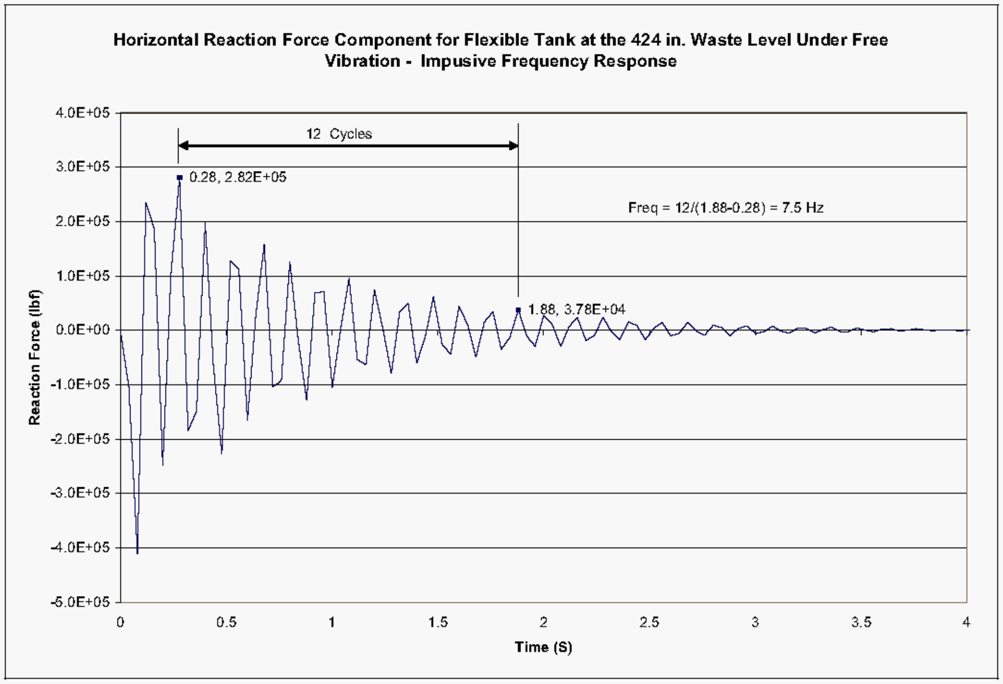


Figure 5-3. Horizontal Reaction Force for Flexible Tank at the 424 in. Waste Level Under Free Oscillation –Impulsive Frequency Response.



5.1.2 Vertical Excitation

The peak vertical hydrodynamic forces for the flexible tank calculated via Equation 4.57 of BNL 1995 with the instantaneous accelerations replaced by the appropriate spectral accelerations and the impulsive and convective components combined via the SRSS rule. The theoretical maximum vertical hydrodynamic force based on spectral accelerations from the 4% damped spectrum is 5.29 x 10^6 lbf.

The total vertical reaction force due to vertical excitation of the ANSYS model is shown as Figure 5-4. The maximum total force is 2.30 x 10^7 lbf, or 5% greater than the theoretical maximum of 2.18 x 10^7 lbf. However, the maximum hydrodynamic force is 6.5 x 10^6 lbf, which is 23% greater than the theoretical value.

The breathing mode frequency response was calculated by subtracting the waste weight from the total vertical reaction force when the tank was subjected to gravity loading. The breathing mode frequency is shown as Figure 5-5. The reaction force is shown in kips, but it is the frequency that is of interest. The frequency calculated by ANSYS is 6.6 Hz compared to the theoretical value of 6 Hz.

Figure 5-4. Total Vertical Reaction Forces for the Flexible Tank at Under Vertical Excitation at the 424 in. Waste Level.

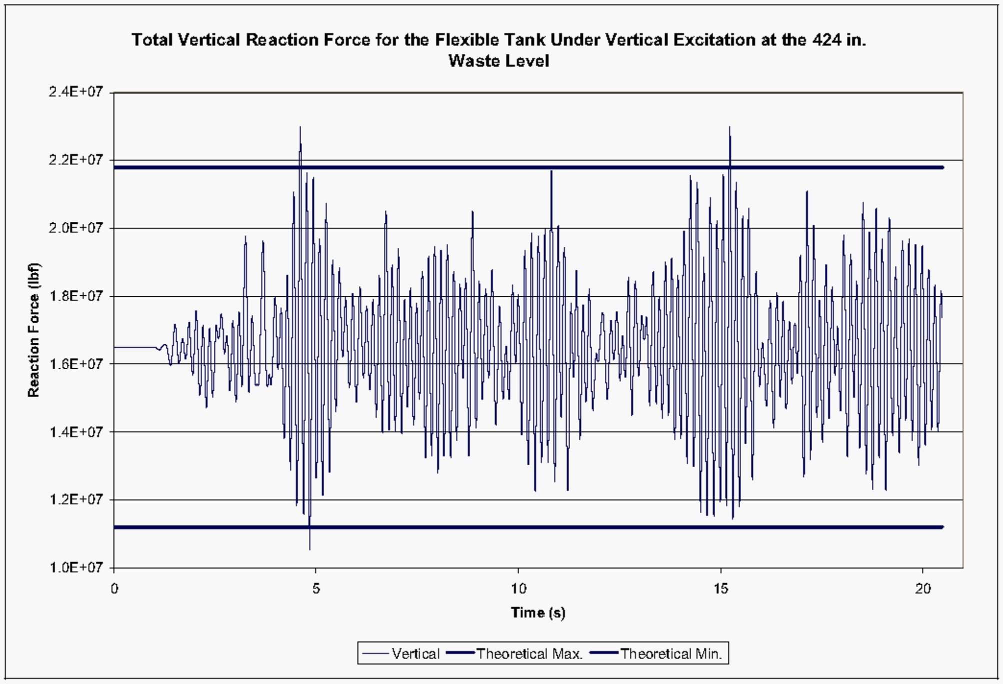
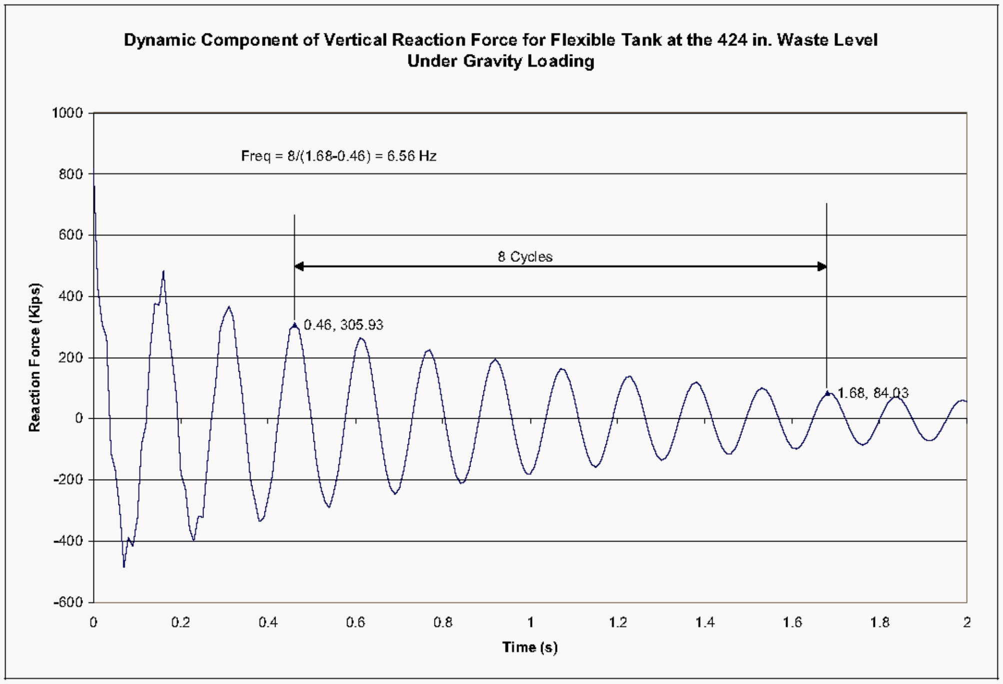


Figure 5-5. Dynamic Component of Vertical Reaction Force for Flexible Tank at the 424 in. Waste Level Under Gravity Loading – Breathing Mode Frequency Response.



5.2 WASTE PRESSURES

Waste pressure time histories and maximum and minimum waste pressure plots for horizontal and vertical excitation are presented in the following two sections.

5.2.1 Horizontal Excitation

The theoretical peak hydrodynamic pressures due to horizontal excitation are given by Equation 4.24 of BNL 1995. The total pressures are the sum of the hydrostatic pressures and the hydrodynamic pressures. The hydrostatic, peak hydrodynamic and peak total pressures for the elements at 0 and 45° from the plane of excitation are shown in Table 5-1 and Table 5-2. The maximum theoretical pressure for the elements located 90° from the plane of excitation is simply the hydrostatic pressures shown in Table 3-1 because the theoretical hydrodynamic pressures are zero at θ=90°.

Table 5-1. Theoretical Waste Pressures for Horizontal Excitation in the Flexible Tank at 424 in. Waste Level for Elements at θ=0.

Normalized Height from Tank Bottom (z/H_l)	Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Pressure (psi gage)	Peak Total Pressure (psi gage)
0.95	5521	1.4	4.0	5.4
0.85	5541	3.8	7.2	11.0
0.77	5561	5.9	9.5	15.4
0.69	5581	8.1	11.3	19.4
0.60	5601	10.3	12.9	23.2
0.52	5621	12.4	14.1	26.5
0.45	5641	14.3	14.9	29.2
0.38	5661	16.2	15.7	31.9
0.30	5681	18.3	16.3	34.6
0.21	5701	20.5	16.8	37.3
0.13	5721	22.7	17.1	39.8
0.06	5741	24.5	17.2	41.7

Table 5-2. Theoretical Waste Pressures for Horizontal Excitation in the Flexible Tank at 424 in. Waste Level for Elements at θ=45°.

Normalized Height from Tank Bottom (z/H_l)	Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Pressure (psi gage)	Peak Total Pressure (psi gage)
0.95	5526	1.4	2.8	4.2
0.85	5546	3.8	5.1	8.9
0.77	5566	5.9	6.7	12.6
0.69	5586	8.1	8.0	16.1
0.60	5606	10.3	9.1	19.4
0.52	5626	12.4	9.9	22.3
0.45	5646	14.3	10.6	24.9
0.38	5666	16.2	11.1	27.3
0.30	5686	18.3	11.5	29.8
0.21	5706	20.5	11.9	32.4
0.13	5726	22.7	12.1	34.8
0.06	5746	24.5	12.2	36.7

The pressure time histories for the ANSYS model waste elements along the tank wall at θ=0 are shown in Figure 5-6, and the pressure time histories for the elements at θ=45 and 90° from the plane of excitation are shown in Figure 5-8, and Figure 5-10, respectively. All ANSYS simulations reported were run at gage pressure, and comparison of the static and dynamic pressures shown in Table 5-1 and Table 5-2 show that negative pressures are predicted for elements in the upper portion of the waste at θ=0 and 45°. Because the waste is modeled as an elastic material, negative pressures (i.e. tensile stresses) are supported by the model, and are realized as shown in the time history plots.

Pressure time histories for the four upper elements in the waste at θ=0 are presented as Figure 5-7. The data not only show negative pressures, but also show that the static pressures of elements 5521 and 5541, as well as 5561 and 5581 do not have the proper spacing. Comparison with Table 5-1 shows that the static pressure of element 5521 is slightly high and the pressure of element 5541 is slightly low. The same relationship exists for the pressures in elements 5561 and 5581. Pressure time histories for the four upper elements in the waste at θ=45° are presented as Figure 5-9. The same behavior is exhibited for these four elements. To a somewhat lesser degree, the response also exists for the four upper elements at θ=90° as seen in Figure 5-10.

Figure 5-6. Waste Pressures Time Histories for the Flexible Tank at the 424 in. Waste Level for Horizontal Excitation at θ=0.

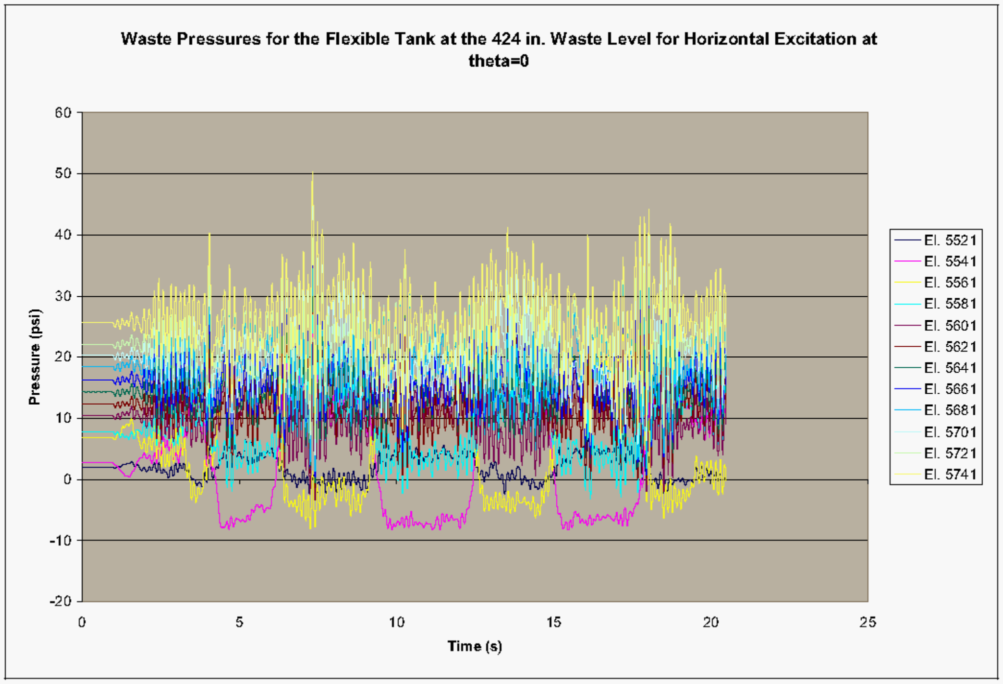


Figure 5-7. Selected Element Pressure Time Histories for the Flexible Tank at the 424 in. Waste Level for Horizontal Excitation at θ=0.

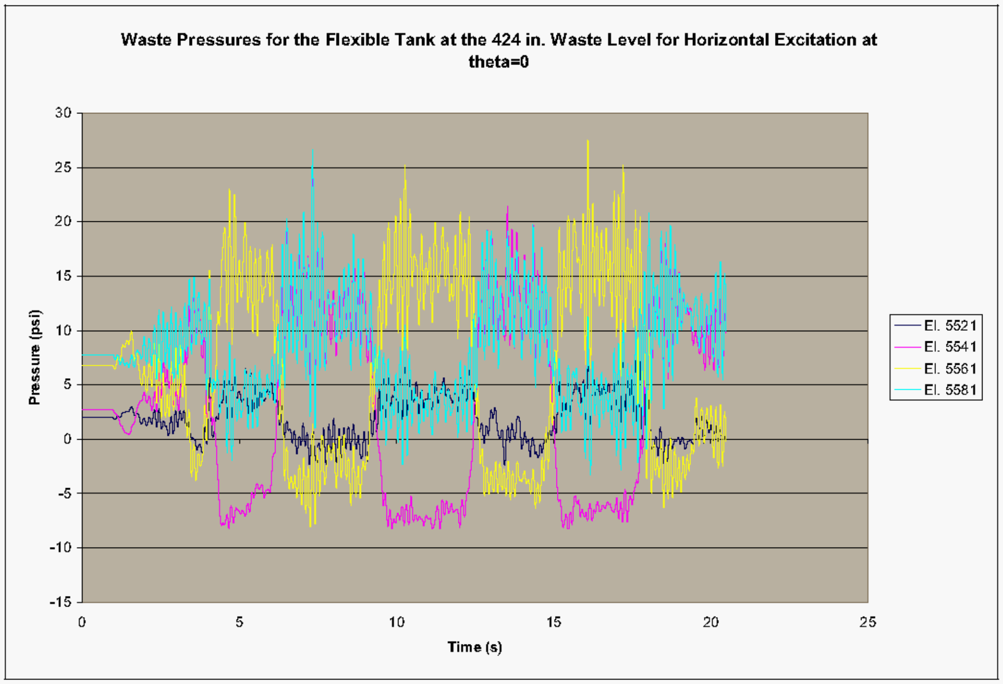


Figure 5-8. Waste Pressure Time Histories for the Flexible Tank at the 424 in. Waste Level for Horizontal Excitation at θ=45°.

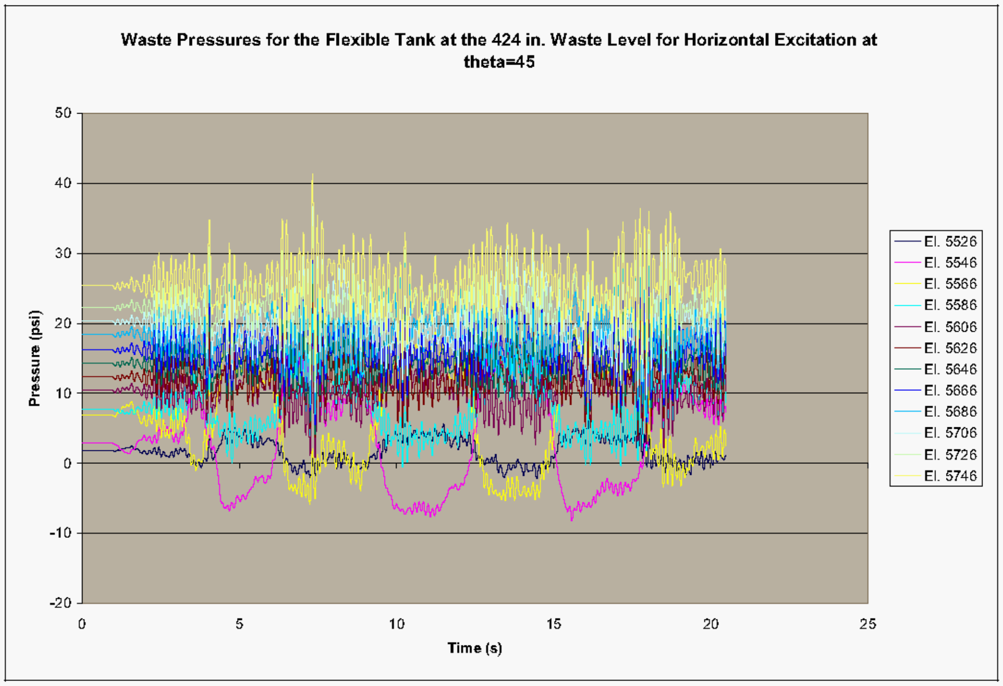


Figure 5-9. Selected Element Pressure Time Histories for the Flexible Tank at the 424 in. Waste Level for Horizontal Excitation at θ=45°

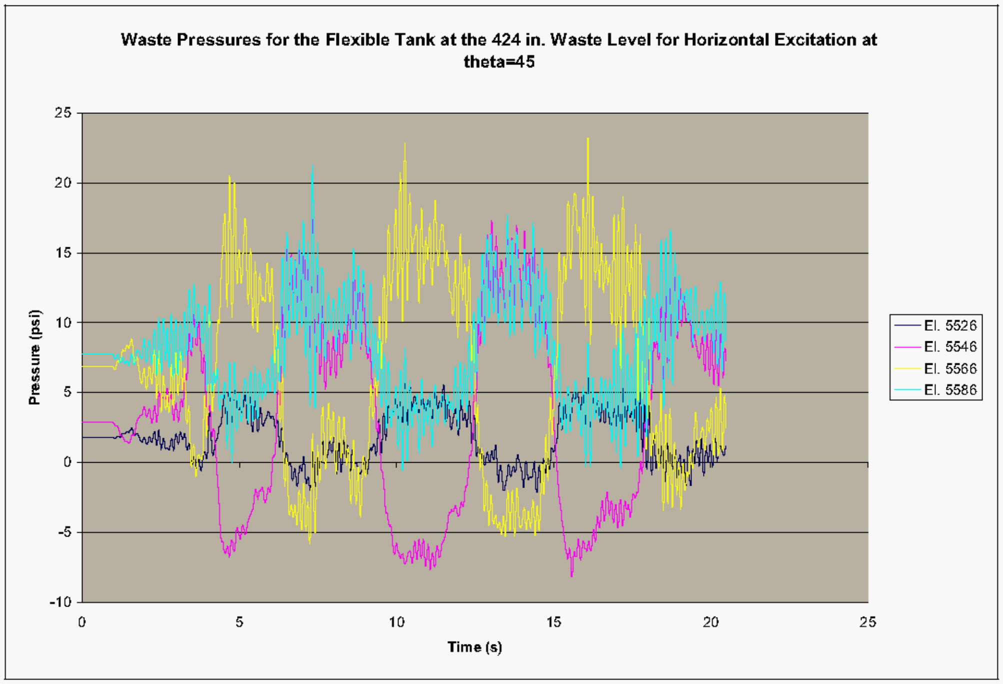
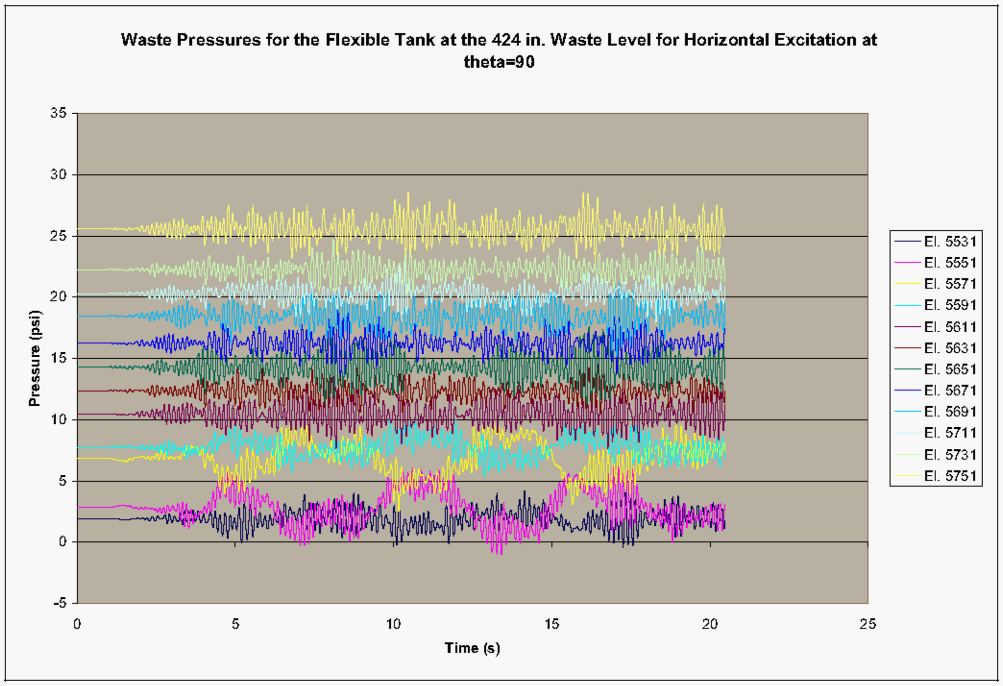


Figure 5-10. Waste Pressures Time Histories for the Flexible Tank at the 424 in. Waste Level for Horizontal Excitation at θ=90°.



Plots of the actual (that is, as predicted by ANSYS) and theoretical maximum and minimum waste pressures at θ=0, 45, and 90° are shown in Figure 5-11 through

Figure 5-13. The plots show that ANSYS tends to over-predict the maximum pressures and that the differences between theoretical and actual peak pressures tend to be greater closer to the waste free surface.

Figure 5-11. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of the Flexible Tank at 424 in. Waste Level and θ=0.

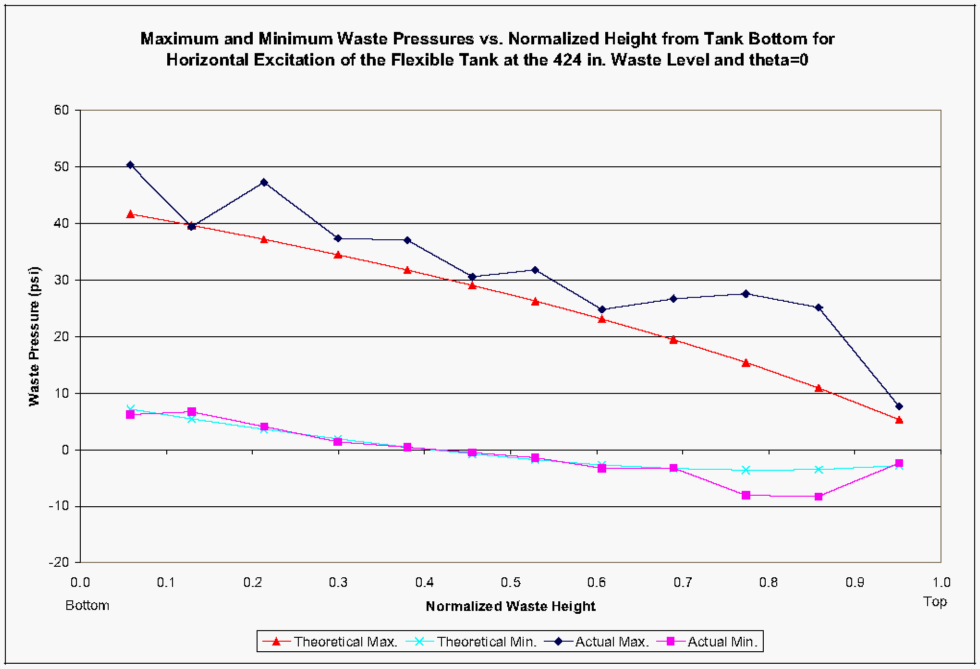


Figure 5-12. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of the Flexible Tank at 424 in. Waste Level and θ=45°.

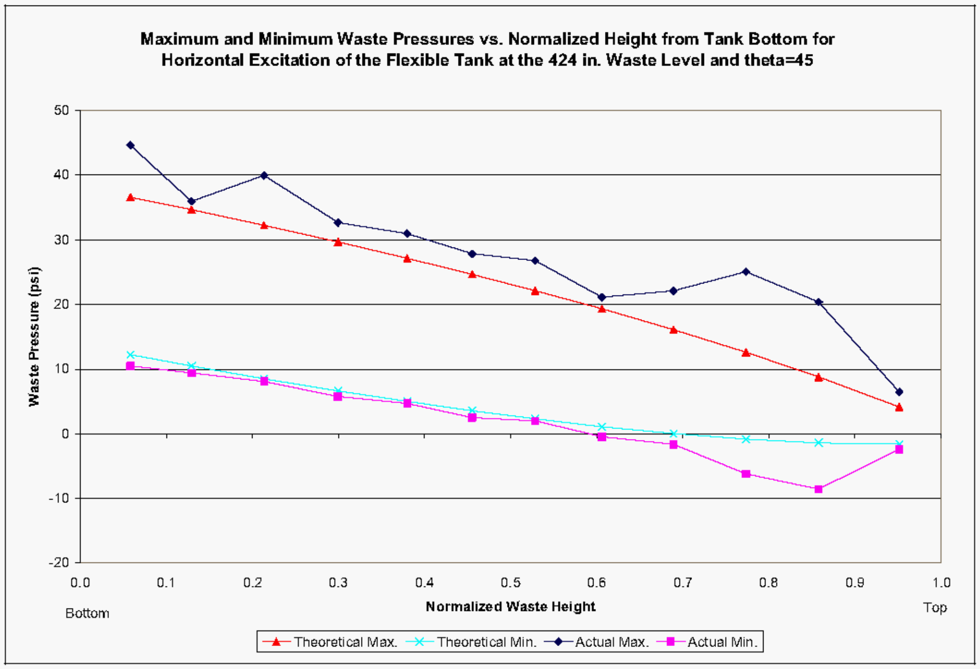
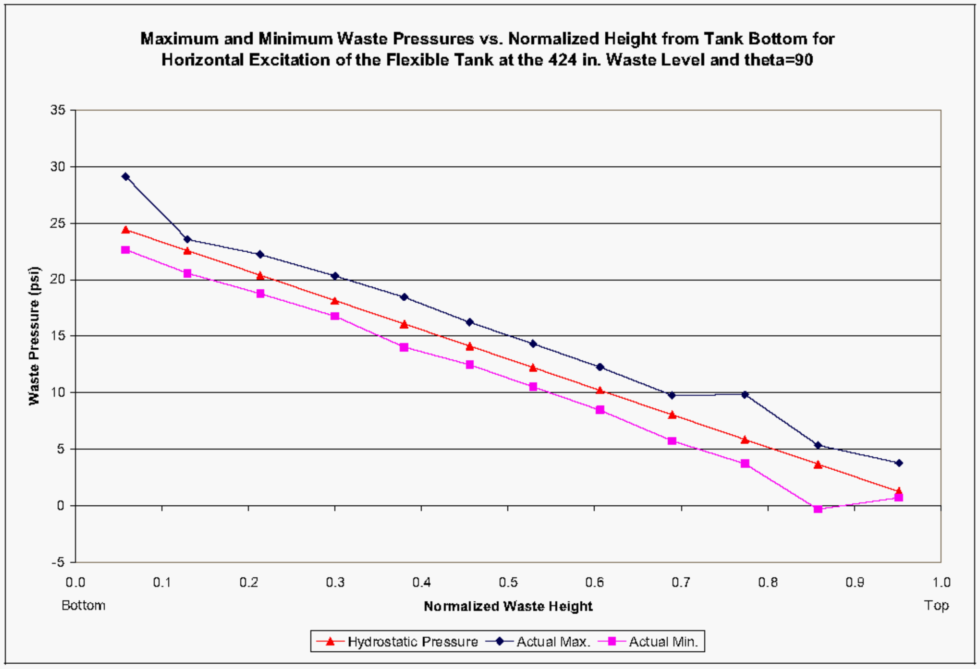


Figure 5-13. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of the Flexible Tank at 424 in. Waste Level and θ=90°.



5.2.2 Wall and Base Pressures Due to Vertical Excitation

The maximum hydrodynamic pressures induced by the waste on the tank wall and base due to vertical excitation depend on the vertical and radial location in the waste, respectively. The peak wall pressures are given by Equation 4.52 of BNL 1995, and the peak base pressures are given by Equation 4.55 of BNL 1995. The theoretical wall pressures are shown in Table 5-3.

Table 5-3. Theoretical Maximum Absolute Wall Pressures for Vertical Excitation in at the 424 in Waste Level.

Normalized Height from Tank Bottom (z/H_l)	θ=0 Element No.	θ=45° Element No.	θ=90° Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Wall Pressure (psi gage)	Peak Total Pressure (psi gage)
0.95	5521	5526	5531	1.4	0.9	2.3
0.85	5541	5546	5551	3.8	2.5	6.3
0.77	5561	5566	5571	5.9	3.9	9.8
0.69	5581	5586	5591	8.1	5.2	13.3
0.60	5601	5606	5611	10.3	6.5	16.8
0.52	5621	5626	5631	12.4	7.5	19.9
0.45	5641	5646	5651	14.3	8.4	22.7
0.38	5661	5666	5671	16.2	9.2	25.4
0.30	5681	5686	5691	18.3	9.9	28.2
0.21	5701	5706	5711	20.5	10.4	30.9
0.13	5721	5726	5731	22.7	10.8	33.5
0.06	5741	5746	5751	24.5	11.0	35.5

The pressure time histories for the waste elements of the ANSYS model that are adjacent to the tank wall at θ=0, 45, and 90° are shown in Figure 5-14, Figure 5-15, and Figure 5-16, respectively. The three plots are very similar to each other as expected since the responses at the three angular locations should be the same. The hydrostatic pressures of the top four waste elements at each location show the same behavior as noted in Section 5.2.1.

Figure 5-14. Waste Pressure Time Histories for the Flexible Tank at the 424 in. Waste Level for Vertical Excitation for θ=0.

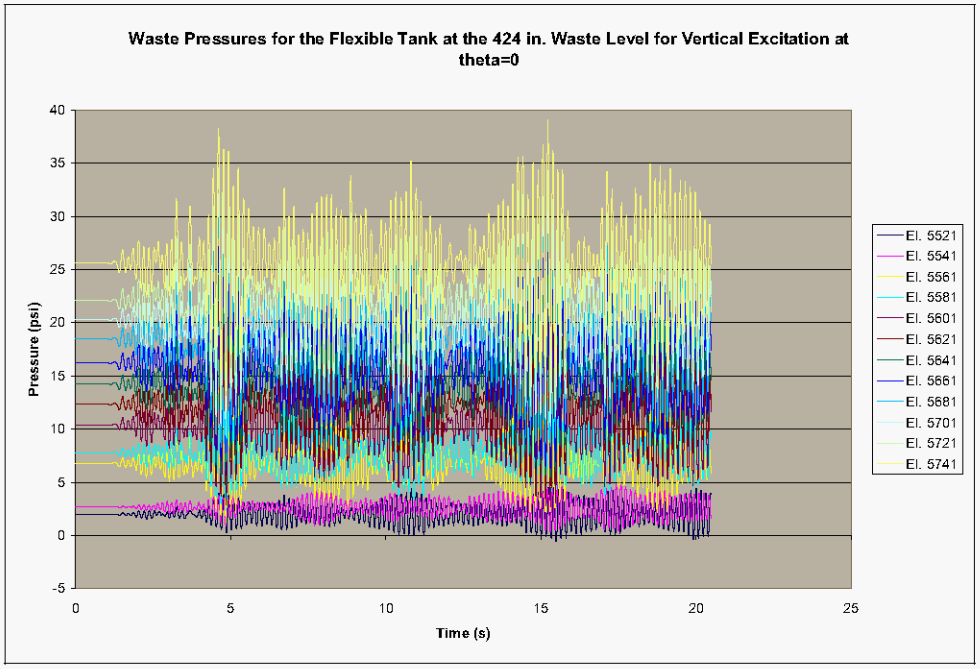


Figure 5-15. Waste Pressure Time Histories for the Flexible Tank at the 424 in. Waste Level for Vertical Excitation for θ=45°.

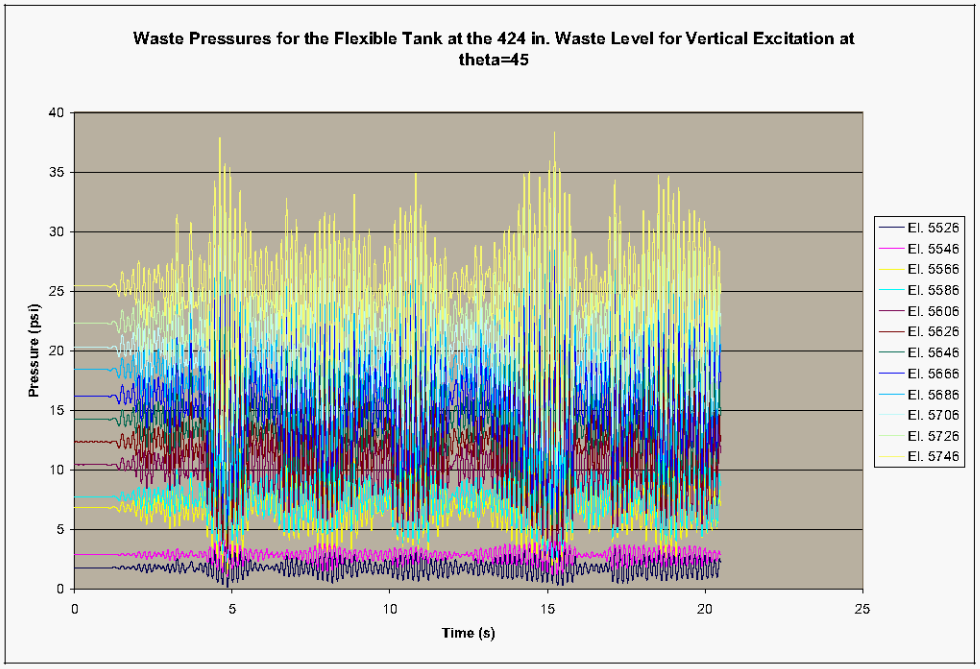
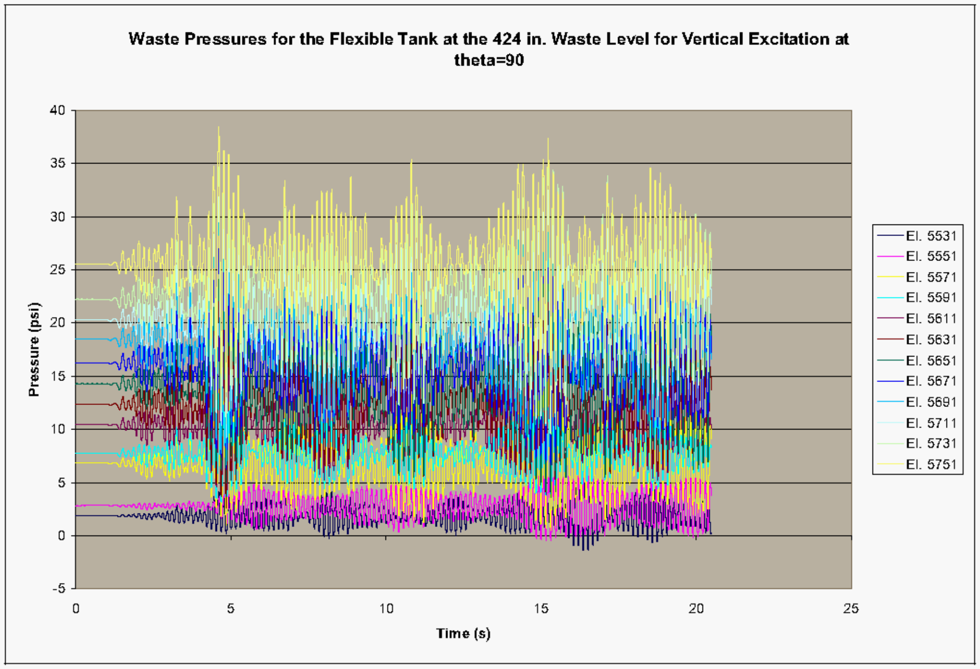


Figure 5-16. Waste Pressure Time Histories for the Flexible Tank at the 424 in. Waste Level for Vertical Excitation for θ=90°.



A plot of the maximum and minimum waste pressures as a function of waste depth is shown in Figure 5-17. At each elevation, the plotted pressure is the maximum or minimum across all angular locations in the model. The results show reasonably good agreement with theory and tend to over-predict the peak pressures.

The pressure time history for a waste element at the bottom central portion of the tank (element 5781) is shown as Figure 5-18. The theoretical hydrostatic pressure for element 5781 is 26.0 lbf/in^2, and the theoretical peak hydrodynamic pressure is 8.5 lbf/in^2. That is, the predicted maximum and minimum pressures at this location are 34.5 and 17.5 lbf/in^2, respectively. The maximum and minimum values shown in Figure 5-18 are 34.3 and 18.8 lbf/in^2, respectively.

Figure 5-17. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for the Flexible Tank at the 424 in. Waste Level Under Vertical Excitation.

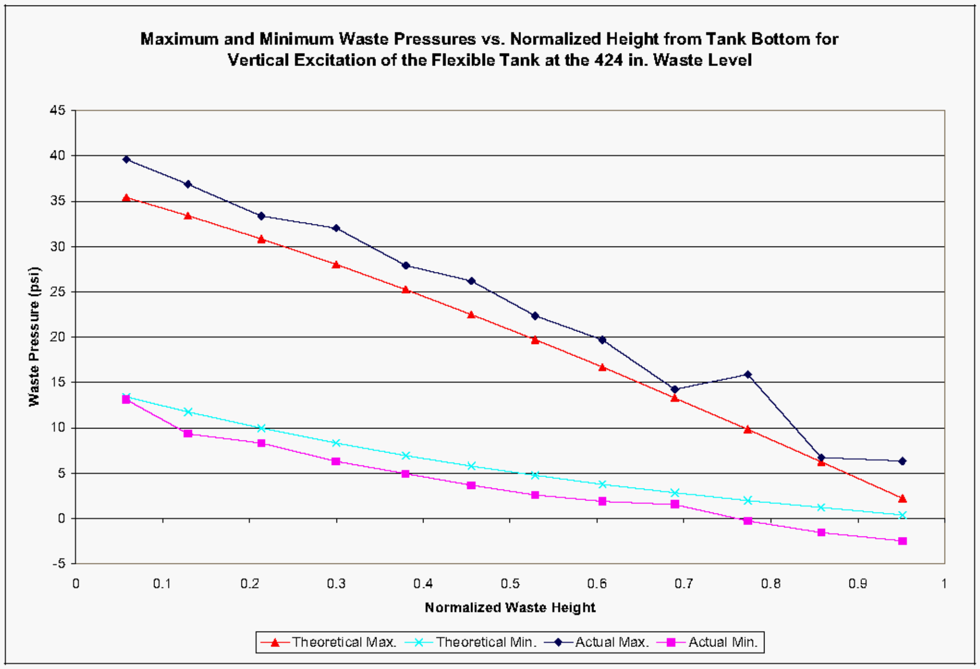
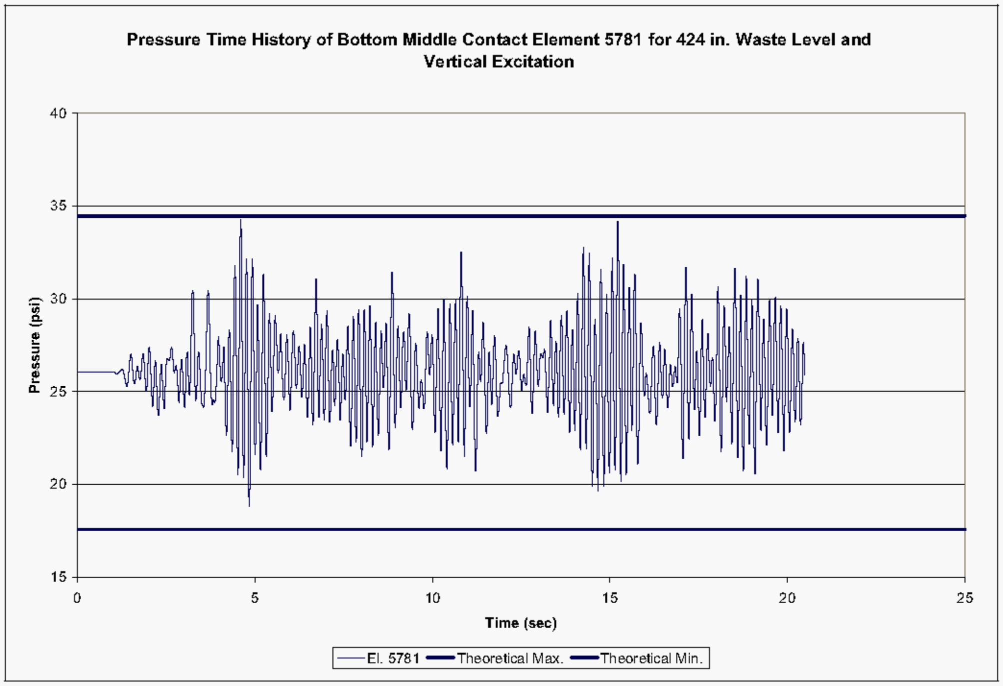


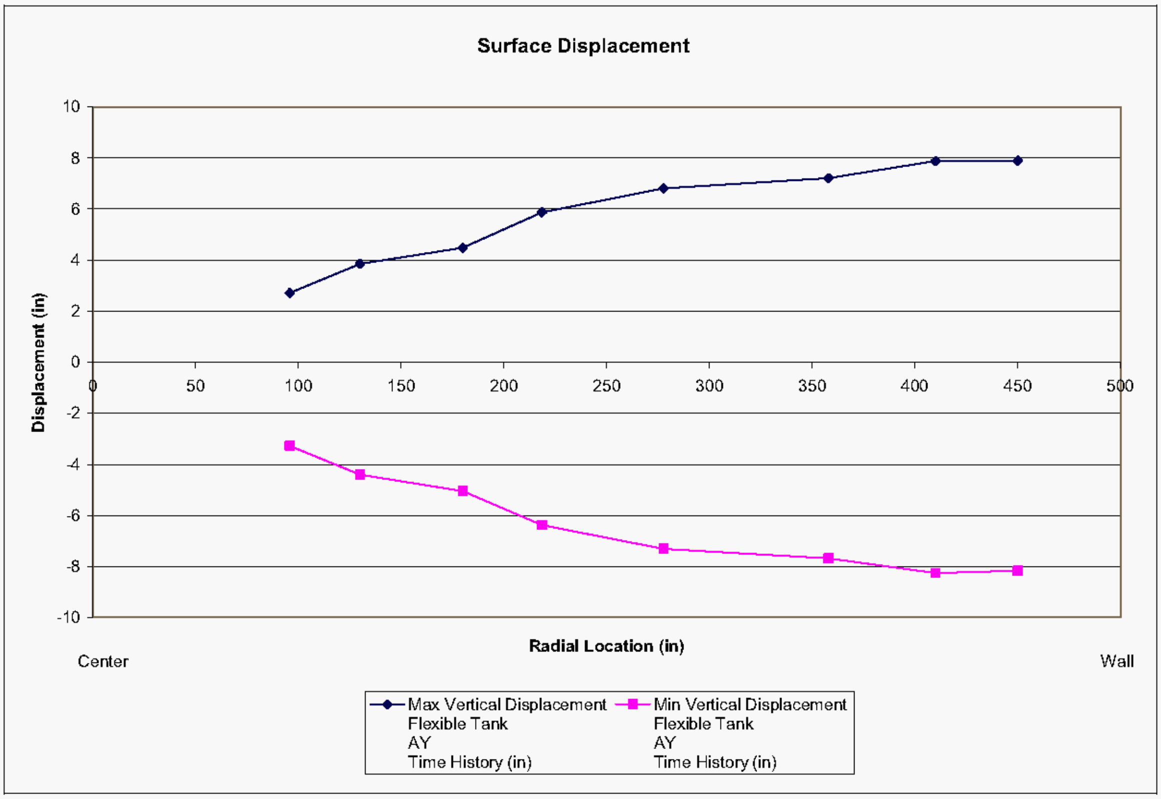
Figure 5-18. Waste Pressure Time Histories for the Bottom Center Waste Element 5781 for the Flexible Tank at the 424 in. Waste Level and Vertical Excitation.



5.3 MAXIMUM SLOSH HEIGHT RESULTS

The maximum slosh height over all surface waste elements regardless of time is shown as Figure 5-19. According to Equation 4.60 of BNL 1995, the maximum predicted slosh height due to horizontal excitation is 23.7 in. The maximum slosh height from the simulation is approximately 8 in., or 1/3 of the open top theoretical value. As was the case for the rigid tank models, the ability to accurately predict slosh heights and the associated convective response is a limitation of the ANSYS flexible tank model.

Figure 5-19. Maximum Slosh Height Time-Histories for the Flexible Tank at the 424 in. Waste Level.



5.4 ELEMENT STRESSES

Mid-plane or membrane hoop stress is shown in Figure 5-20, Figure 5-21, and Figure 5-22, for tank wall elements at θ=0, 45, and 90°, respectively. Although some checks exist for the expected stress values, because of the complexity of the structure, the stress fields will be more complicated that the fluid pressure fields. The primary reason for assuming a uniform wall thickness for the benchmark primary tank model was to simplify the distribution of stress in the tank wall and particular to simplify the hoop stress distribution that can be approximated as

$$\sigma_{hoop} = \frac{pr}{t},$$

where p is the fluid pressure, r is the tank radius, and t is the tank wall thickness. This relationship is, of course, expected to breakdown near the upper and lower portions of the tank wall due to local end effects, but should give a good approximation in the central portion of the tank wall.

A comparison between membrane hoop stress and the expected value of that stress for a tank wall element at mid-height in the wall is shown as Figure 5-23. The hoop stresses are generally as expected and show the proper dependence on the angle from the plane of excitation.

5.4.1 Horizontal Excitation Run

Figure 5-20. Mid-Plane Hoop Stress for the Flexible Tank at the 424 in. Waste Level at θ=0.

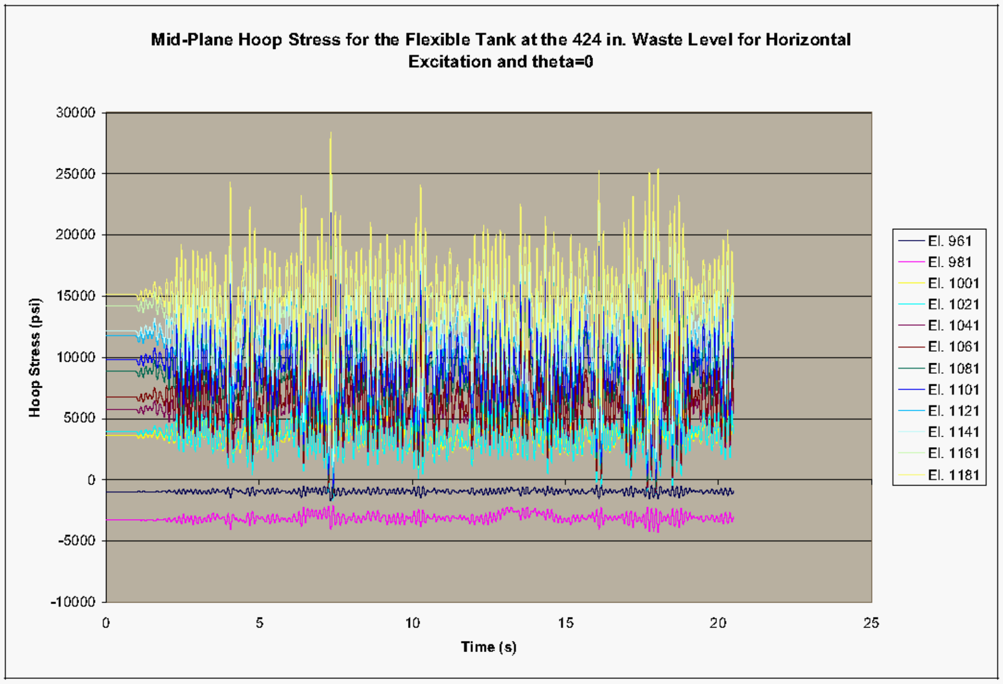


Figure 5-21. Mid-Plane Hoop Stress for the Flexible Tank at the 424 in. Waste Level at θ=45°.

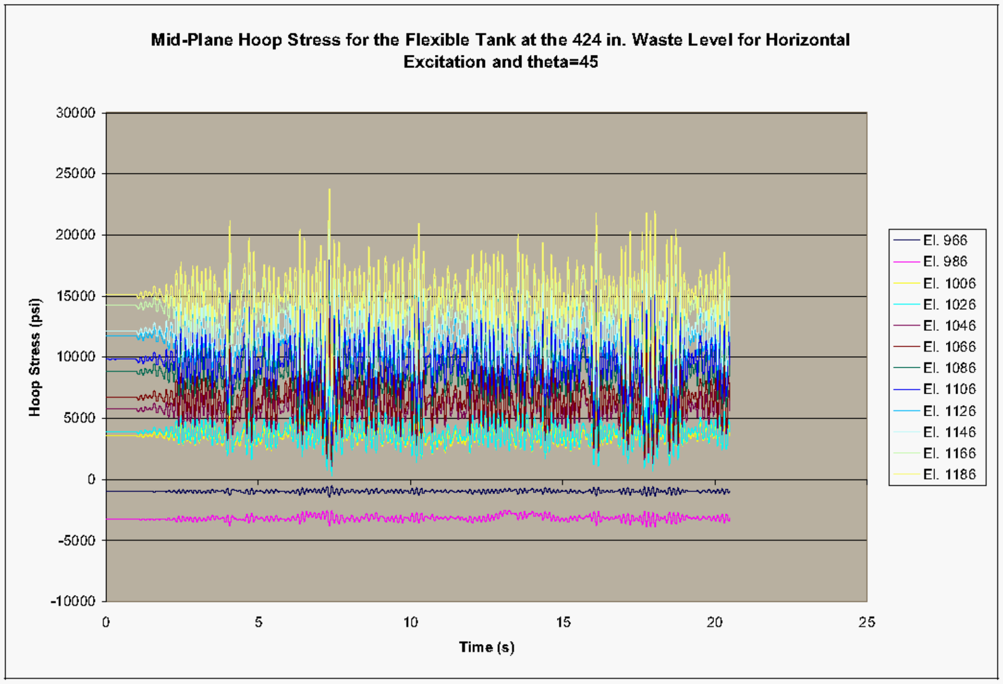


Figure 5-22. Mid-Plane Hoop Stress for the Flexible Tank at the 424 in. Waste Level at θ=90°.

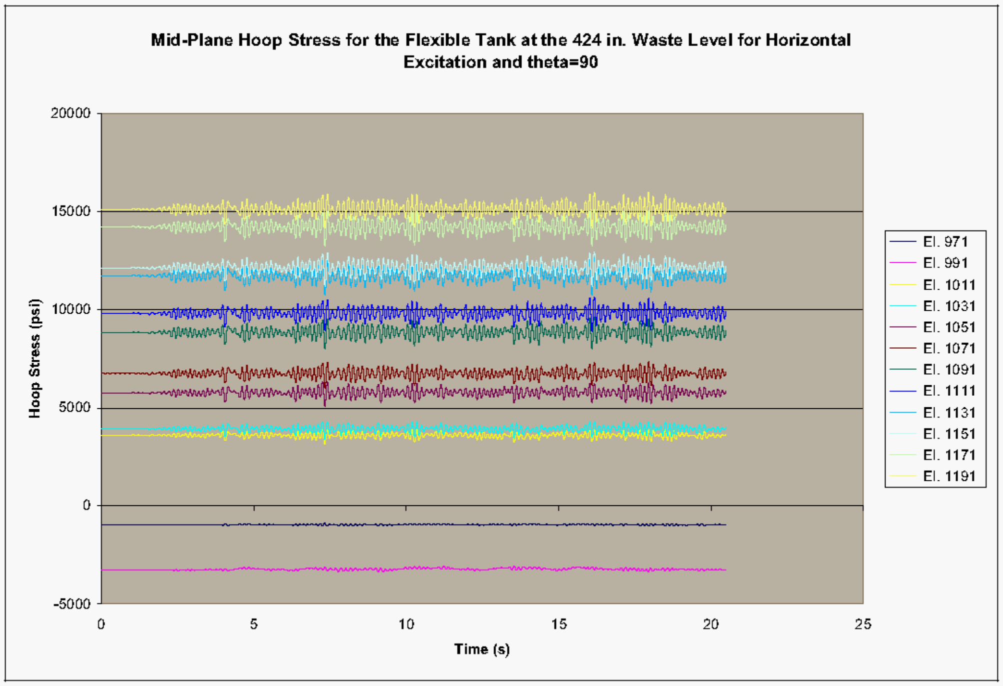
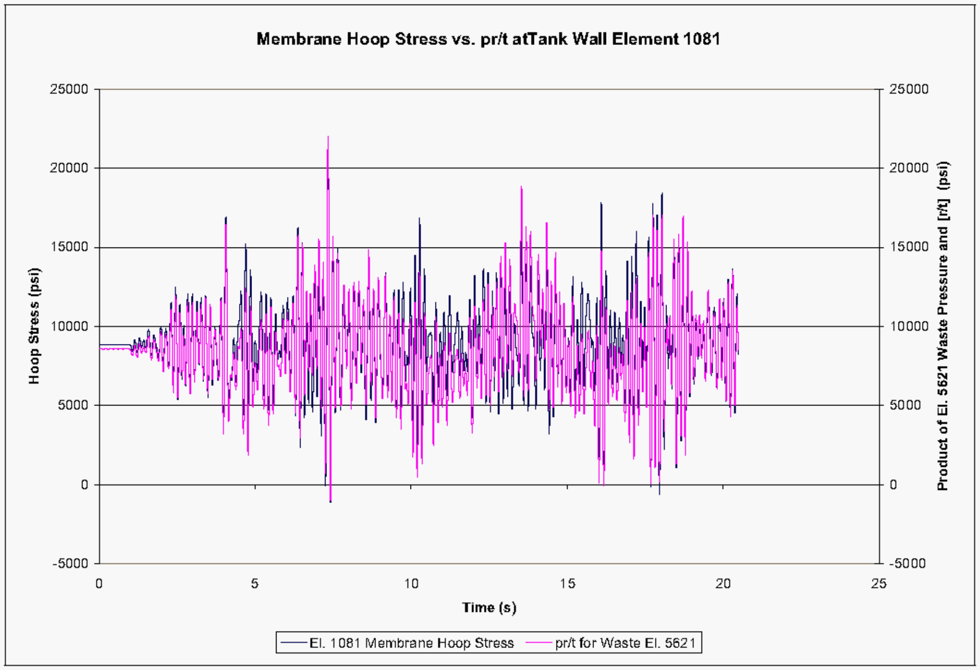


Figure 5-23. Comparison of Membrane Hoop Stress in Tank Wall Element 1081 to pr/t for Waste Element 5621 at Wall Mid-Height and θ=0.



6.0 FLEXIBLE TANK ANSYS MODEL AT 460 INCH WASTE LEVEL

The response of the tank and contained liquid to seismic excitation with the liquid initially at the 460 in. level does not have a closed form analytical solution because of the interaction of the liquid free surface with the curved surface of the tank dome. However, the solutions obtained with ANSYS will be compared to the theoretical solution for the open tank with the hinged top condition and 460 in. waste level as well as with the Dytran solution at the 460 in. level.

The ANSYS simulation for vertical seismic excitation was inadvertently run with a waste level of 452 rather than 460 in., and the results presented for vertical input are for the 452 in. waste level. For vertical input, the difference between the two waste levels is minor, and simulations were not re-run at the 460 in. waste level. However, for consistency, the ANSYS results were compared to theoretical results for an open top tank at the 452 in. waste level. Similarly, the free oscillation convective and impulsive frequency responses were performed at the 452 in. waste level.

6.1 HYDRODYNAMIC FORCES

6.1.1 Horizontal Excitation

The total horizontal reaction force time history for the tank under horizontal seismic input is shown as Figure 6-1. Figure 6-2 shows the total horizontal reaction force for the rigid tank model when subjected to horizontal free oscillation. The convective reaction was determined from free oscillation of the rigid tank, so Figure 6-2 is a duplicate of Figure 4-2 and is shown in this section for convenience of the reader. The plot shows a fundamental convective frequency of 0.192 Hz, slightly less than the open top theoretical value of 0.2 Hz.

The peak reaction force is 1.05 x 10^7 lbf, which is the same as the theoretically predicted value for the open tank with the hinge top condition at the 460 in. waste level.

Figure 6-2 shows the total horizontal reaction force for the rigid tank model when subjected to horizontal free oscillation. The convective reaction was determined from free oscillation of the rigid tank, so Figure 6-2 is a duplicate of Figure 4-2 and is shown in this section for convenience of the reader. The plot shows a fundamental convective frequency of 0.192 Hz, slightly less than the open top theoretical value of 0.2 Hz.

The impulsive frequency response is shown in Figure 6-3. The impulsive frequency was calculated by subtracting the reaction force for the rigid tank from the reaction force for the flexible tank. Because the reaction force for the rigid tank represents the convective reaction, and the reaction force for the flexible tank is the sum and impulsive and convective components, the difference between the total reaction for the flexible tank and the total (convective) reaction for the rigid tank isolates the impulsive frequency for the flexible tank. The impulsive frequency determined in this manner is 6.5 Hz and compares well to a theoretical value of 6.6 Hz.

Figure 6-1. Total Horizontal Reaction Force for the Flexible Tank Model at the 460 in. Waste Level for Horizontal Seismic Input.

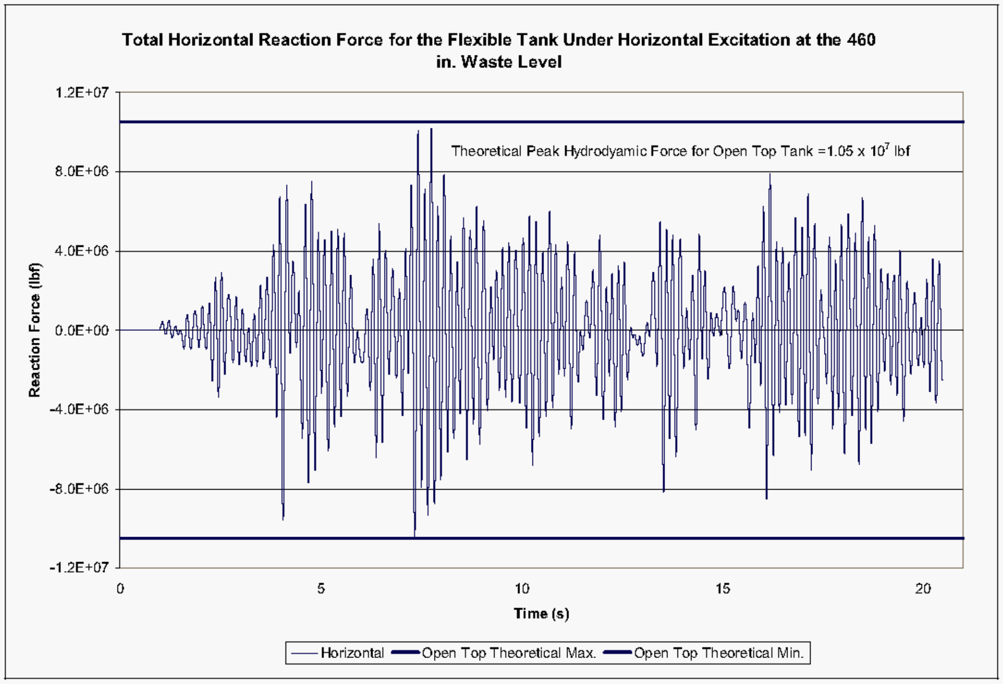


Figure 6-2. Total Horizontal Reaction Force for Rigid Tank at the 452 in. Waste Level Under Free Oscillation – Convective Frequency Response.

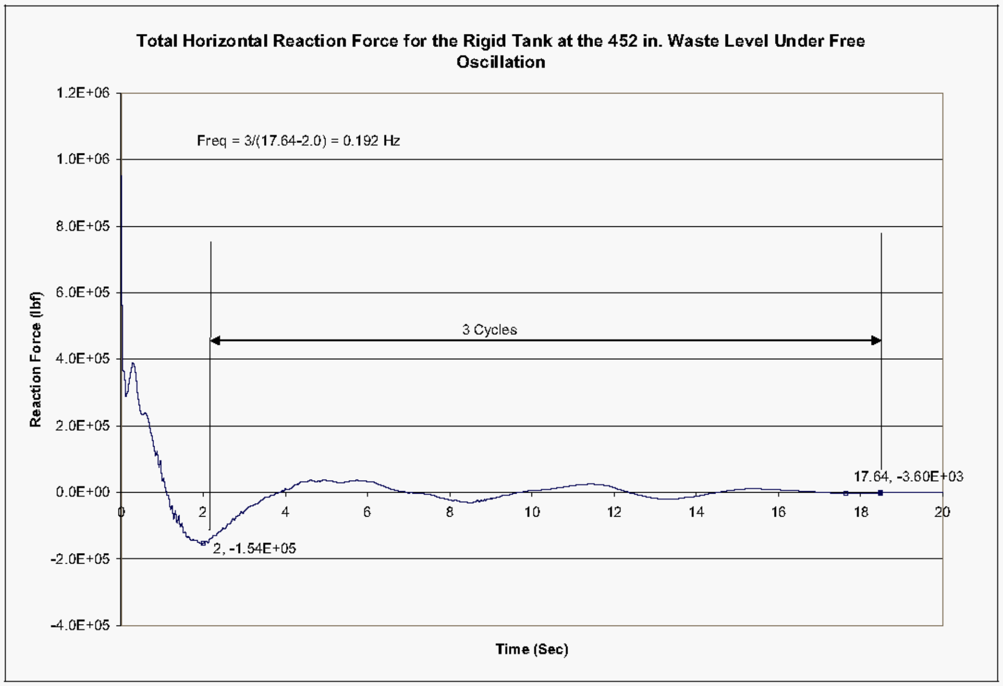
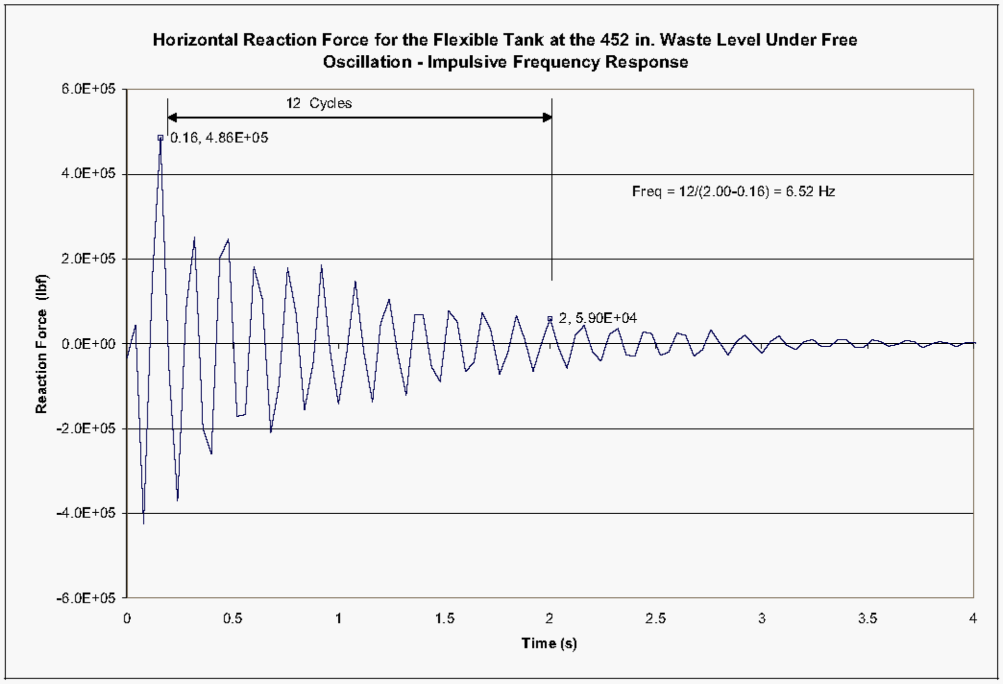


Figure 6-3. Horizontal Reaction Force for Flexible Tank at the 452 in. Waste Level Under Free Oscillation –Impulsive Frequency Response.



6.1.2 Vertical Excitation

The peak vertical reaction force from the ANSYS simulation was 2.45 x 10^7 lbf – 10% greater than the open top theoretical maximum of 2.35 x 10^7 lbf. The maximum dynamic component of the vertical reaction force is 5.6 x 10^6 lbf, or 20% greater than the open top theoretical value of 4.66 x 10^6 lbf. The time history plot of the total vertical reaction force is shown as Figure 6-4.

The breathing mode frequency response was calculated by subtracting the waste weight from the total vertical reaction force when the tank was subjected to gravity loading. The breathing mode frequency is shown as Figure 6-5. The frequency calculated by ANSYS is 5.7 Hz compared to the theoretical value of 5.5 Hz.

Figure 6-4. Total Vertical Reaction Force for the Flexible Tank Model Under Vertical Excitation at the 452 in. Waste Level.

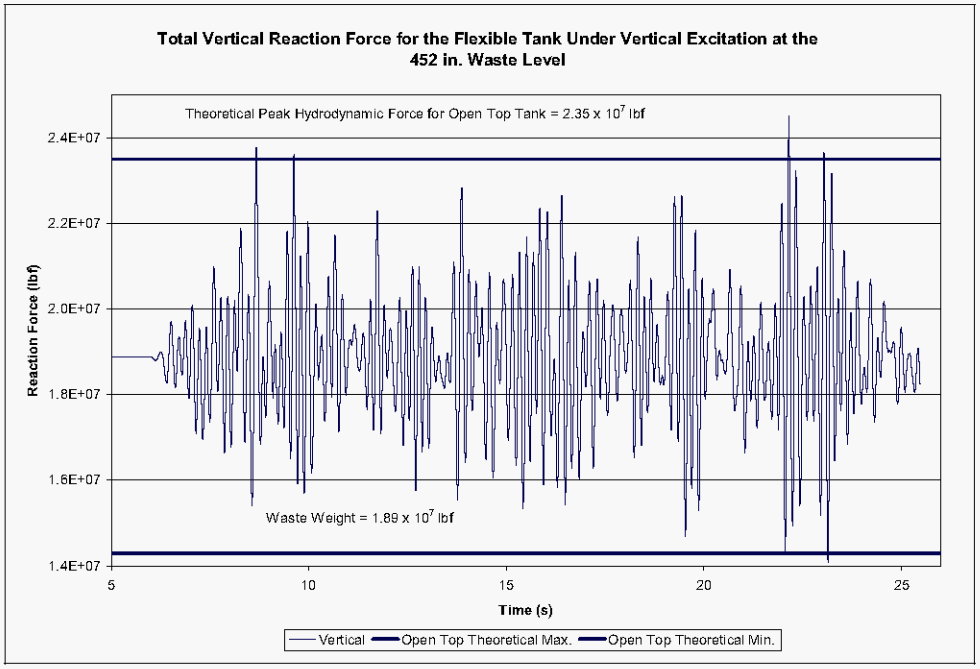
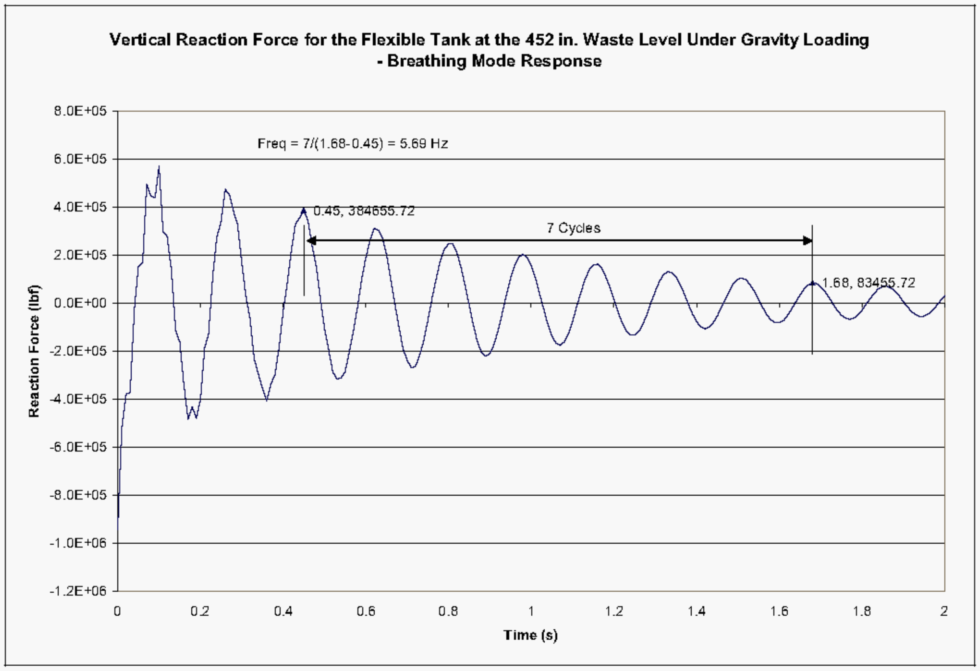


Figure 6-5. Dynamic Component of Vertical Reaction Force for Flexible Tank at the 452 in. Waste Level Under Gravity Loading – Breathing Mode Frequency Response.



6.2 WASTE PRESSURES

Although no closed form solution exists for the 460 in. waste level, theoretical dynamic pressures were calculated using Equation 4.24 of BNL 1995 *based on an open tank with 460 in. of waste and a hinged top condition*. This solution is presented along with the actual results for comparison purposes.

As in Section 5.2, the total pressures are the sum of the hydrostatic pressures and the hydrodynamic pressures. The hydrostatic, peak hydrodynamic and peak total pressures for the elements located 0 and 45° from the plane of excitation are shown in Table 6-1 and Table 6-2. The maximum theoretical pressures for the elements located 90° from the plane of excitation are simply the hydrostatic pressures shown in Table 6-1 because the theoretical hydrodynamic pressures are zero at θ=90°.

Table 6-1. Theoretical Maximum Absolute Waste Pressures for Horizontal Excitation in the Flexible Open Top Tank at 460 in. Waste Level for Elements at θ=0.

Normalized Height from Tank Bottom (z/H_l)	θ=0 Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Pressure (psi gage)	Peak Total Pressure (psi gage)
0.99	5471	0.3	2.8	3.1
0.95	5511	1.4	4.8	6.2
0.87	5551	3.8	8.4	12.3
0.79	5791	6.5	11.6	18.1
0.71	5811	8.8	13.9	22.7
0.63	5831	11.1	15.8	26.9
0.56	5851	13.5	17.3	30.8
0.48	5871	15.7	18.5	34.2
0.42	5891	17.8	19.5	37.3
0.35	5911	19.8	20.2	40.0
0.28	5931	22.0	20.8	42.8
0.20	5951	24.5	21.4	45.9
0.12	5971	26.8	21.7	48.5
0.05	5991	28.8	21.8	50.6

Table 6-2. Theoretical Maximum Absolute Waste Pressures for Horizontal Excitation in the Flexible Open Top Tank at 460 in. Waste Level for Elements at θ=45.

Normalized Height from Tank Bottom (z/H_l)	Θ=45° Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Pressure (psi gage)	Peak Total Pressure (psi gage)
0.99	5476	0.3	2.0	2.3
0.95	5516	1.4	3.4	4.8
0.87	5556	3.8	5.9	9.7
0.79	5796	6.5	8.2	14.7
0.71	5816	8.8	9.8	18.6
0.63	5836	11.1	11.2	22.3
0.56	5856	13.5	12.3	25.8
0.48	5876	15.7	13.1	28.8
0.42	5896	17.8	13.8	31.6
0.35	5916	19.8	14.3	34.1
0.28	5936	22.0	14.7	36.7
0.20	5956	24.5	15.1	39.6
0.12	5976	26.8	15.3	42.1
0.05	5996	28.8	15.4	44.2

6.2.1 Horizontal Excitation

The pressure time histories for the elements adjacent to the tank wall at θ=0, 45, and 90° are shown in Figure 6-6, Figure 6-7, and Figure 6-8, respectively. The predicted static pressure for the upper layer of waste elements is 0.3 lbf/in^2 as shown in Table 6-1. The static pressure predicted by ANSYS is -0.6 lbf/in^2 as shown in Figure 6-6, Figure 6-7, and Figure 6-8, indicating that a slight tensile stress exists in these elements prior to the seismic loading.

The pressure time histories for the two upper most waste elements at θ=0 and 45° are shown in Figure 6-7 and Figure 6-9. Those two plots show that the peak pressures in those elements is much higher than predicted by theory. Moreover, the high peak pressures do not occur at isolated points, but reflect the general response of the waste as predicted by ANSYS.

Figure 6-6. Waste Pressures Time Histories for the Flexible Tank at the 460 in. Waste Level for Horizontal Excitation at θ=0.

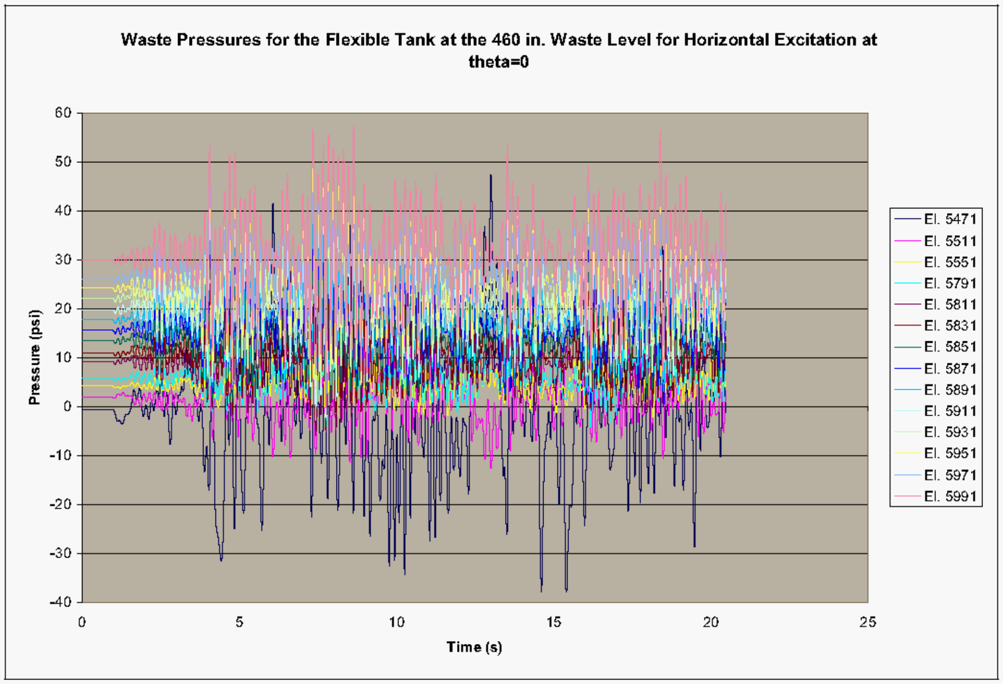


Figure 6-7. Selected Element Pressure Time Histories for the Flexible Tank at the 460 in. Waste Level for Horizontal Excitation at θ=0.

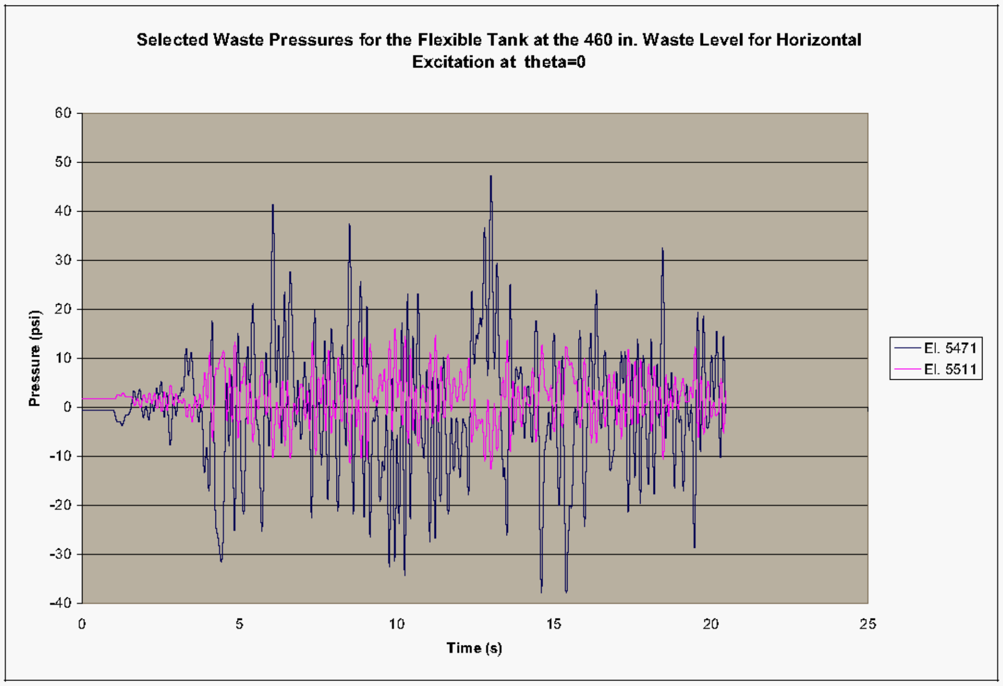


Figure 6-8. Waste Pressures Time Histories for the Flexible Tank at the 460 in. Waste Level for Horizontal Excitation at θ=45°.

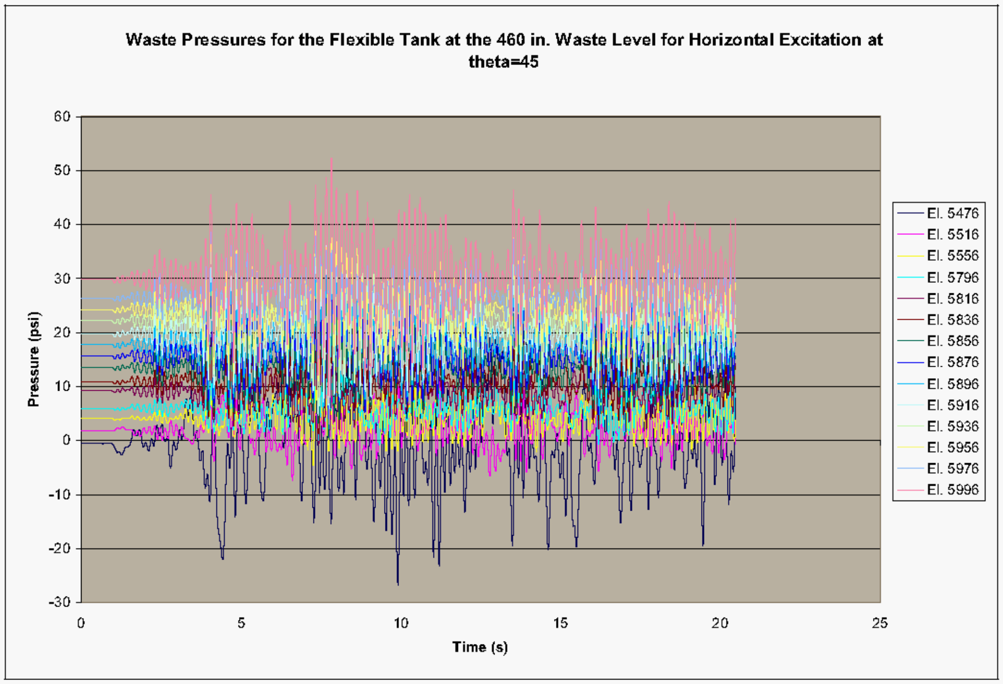


Figure 6-9. Selected Element Pressure Time Histories for the Flexible Tank at the 460 in. Waste Level for Horizontal Excitation at θ=45°.

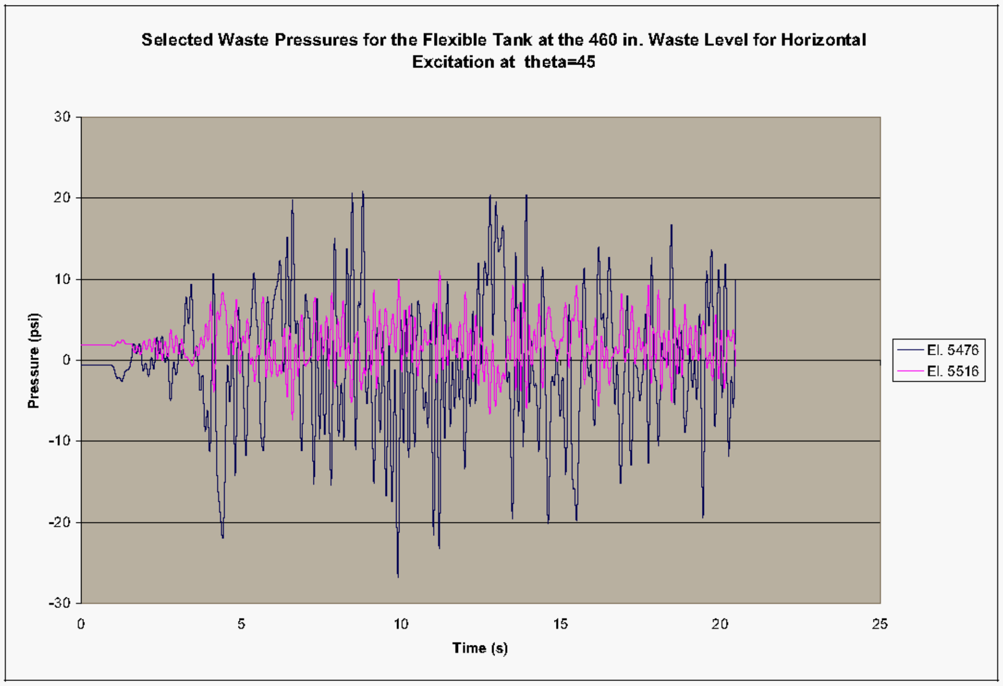
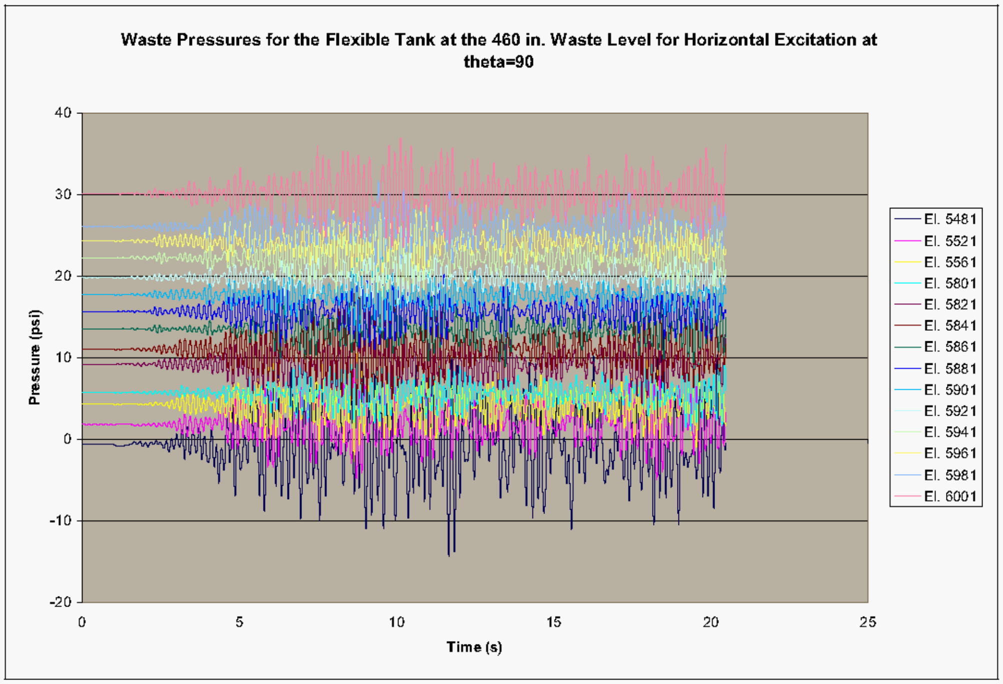


Figure 6-10. Waste Pressures Time Histories for the Flexible Tank at the 460 in. Waste Level for Horizontal Excitation at θ=90°.



Comparisons of the maximum and minimum waste pressures from the computer simulation to the maximum and minimum pressures from the theoretical solution for the open tank at the 460 in. waste level are shown in Figure 6-11, Figure 6-12, and Figure 6-13. The agreement between the actual peak stresses predicted by ANSYS and the theoretical peak stresses is reasonably good, except near the free surface. Again, ANSYS tends to over-predict the peak pressures.

Figure 6-11. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of the Flexible Tank at 460 in. Waste Level and θ=0.

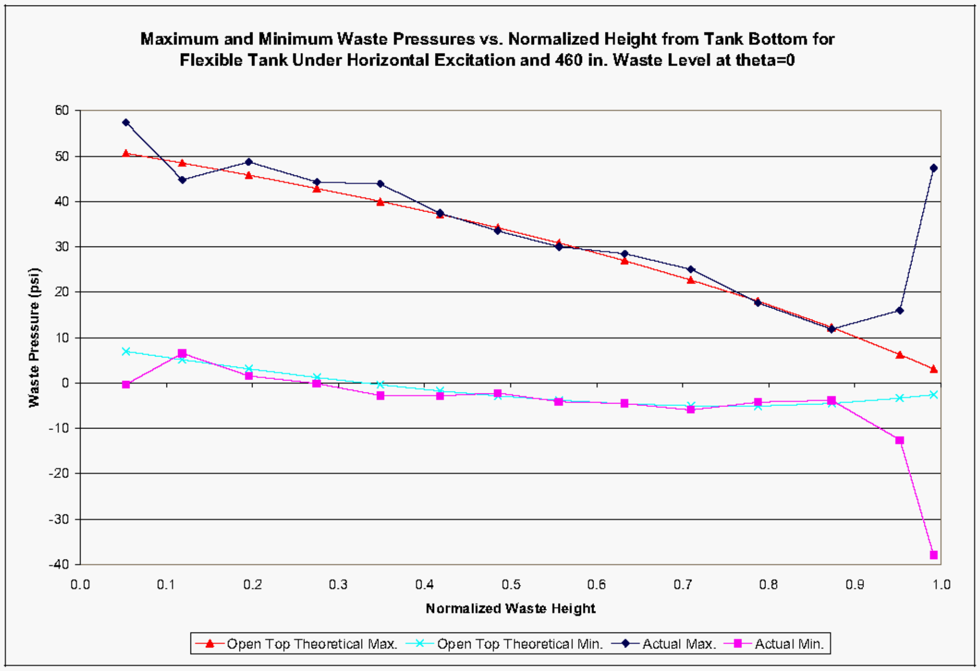


Figure 6-12. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of the Flexible Tank at 460 in. Waste Level and θ=45°.

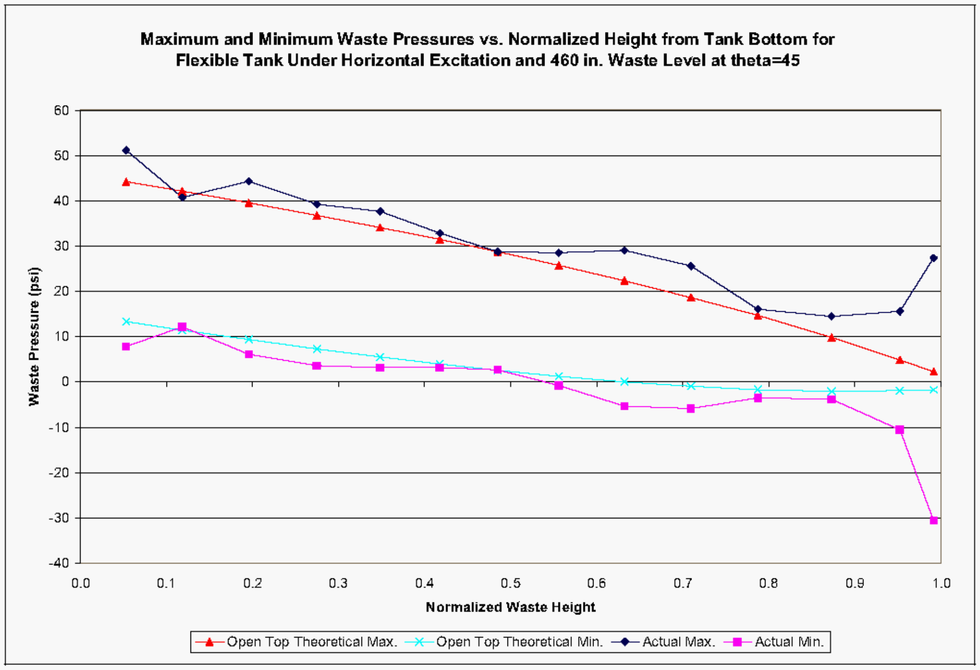
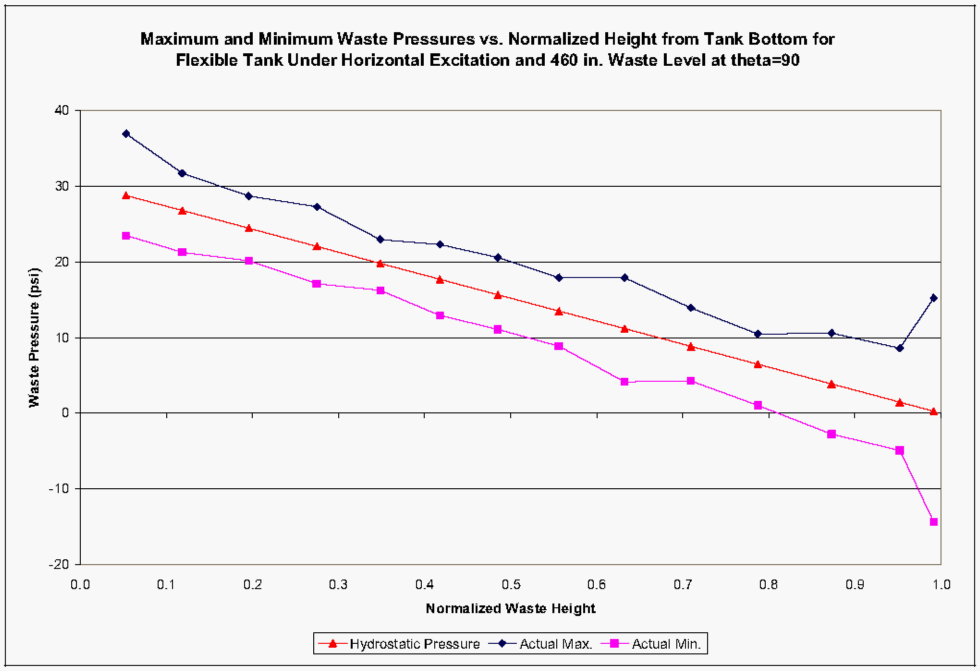


Figure 6-13. Maximum and Minimum Waste Pressures vs. Normalized Height from Tank Bottom for Horizontal Excitation of the Flexible Tank at 460 in. Waste Level and θ=90°.



6.2.2 Wall and Base Pressures Due to Vertical Excitation

Table 6-3. Theoretical Maximum Wall Pressures for Vertical Excitation of an Open Top Flexible Tank at the 452 in. Waste Level.

Normalized Height from Tank Bottom (z/H_l)	θ=0 Element No.	θ=45° Element No.	θ=90° Element No.	Hydrostatic Pressure (psi gage)	Peak Hydrodynamic Wall Pressure (psi gage)	Peak Total Pressure (psi gage)
0.97	6321	6326	6331	0.9	0.5	1.4
0.89	6341	6346	6351	3.3	1.7	5.0
0.80	5731	5736	5741	5.9	2.9	8.8
0.72	5751	5756	5761	8.2	4.0	12.2
0.65	5771	5776	5781	10.6	5.1	15.7
0.57	5791	5796	5801	13.0	6.0	19.0
0.49	5811	5816	5821	15.2	6.9	22.1
0.42	5831	5836	5841	17.2	7.5	24.7
0.35	5851	5856	5861	19.3	8.1	27.4
0.28	5871	5876	5881	21.5	8.7	30.2
0.20	5891	5896	5901	23.9	9.1	33.0
0.12	5911	5916	5921	26.3	9.4	35.7
0.05	5931	5936	5941	28.3	9.5	37.8

The pressure time histories for the waste elements adjacent to the tank wall at θ=0, 45, and 90° are shown in Figure 6-14, Figure 6-14, and Figure 6-16. Minor differences exist in the responses at the 0, 45, and 90° degree locations, but the pressures are very similar as expected since there should be no variation in the response as a function of angular location for vertical excitation.

The pressure time history for element 5971 at the bottom of the tank near the center is shown as Figure 6-17. The plot is included to benchmark the radial variation of waste pressure for vertical seismic excitation of the flexible tank. The theoretical hydrostatic pressure at the centroid of element 5971 is 29.9 lbf/in^2, and the theoretical peak hydrodynamic pressure is 7.7 lbf/in^2. That is, the predicted maximum and minimum pressures at this location are 37.6 and 22.1 lbf/in^2, respectively. The maximum and minimum values shown in Figure 6-17 are 37.3 and 23.5 lbf/in^2, respectively, showing good agreement with the ANSYS results.

A plot of the maximum and minimum waste pressures as a function of waste depth is shown in Figure 6-18. The plot shows that there is more oscillation in the in the pressure time histories than predicted by theory since the maximums are greater than predicted, and the minimums are less than predicted by open top theory.

Figure 6-14. Waste Pressure Time Histories for the Flexible Tank at the 452 in. Waste Level for Vertical Excitation at θ=0.

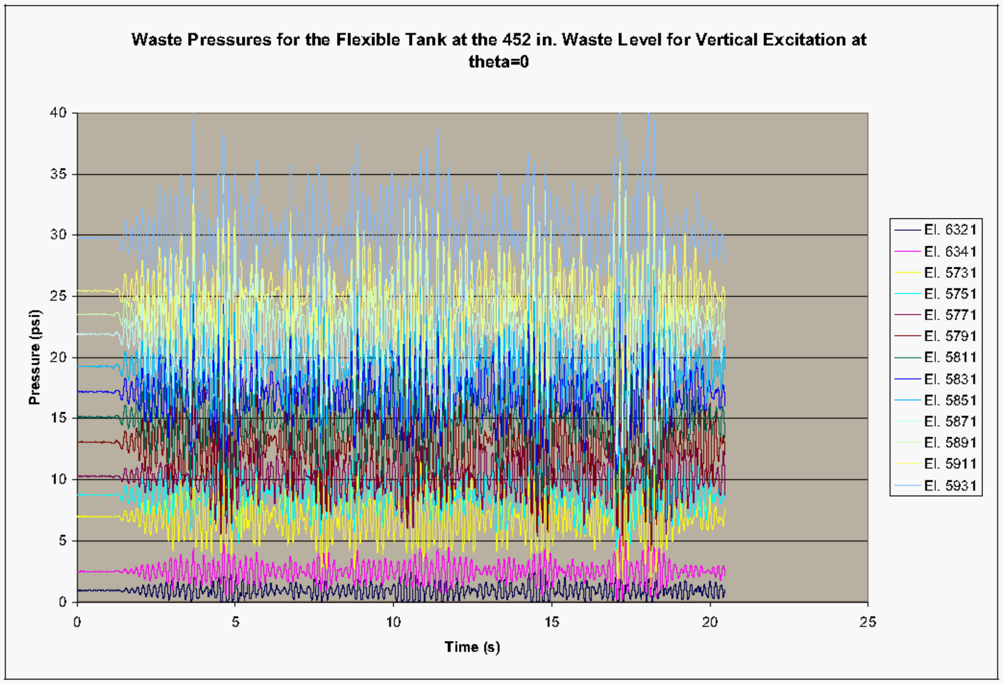


Figure 6-15. Waste Pressure Time Histories for the Flexible Tank at the 452 in. Waste Level for Vertical Excitation at θ=45°.

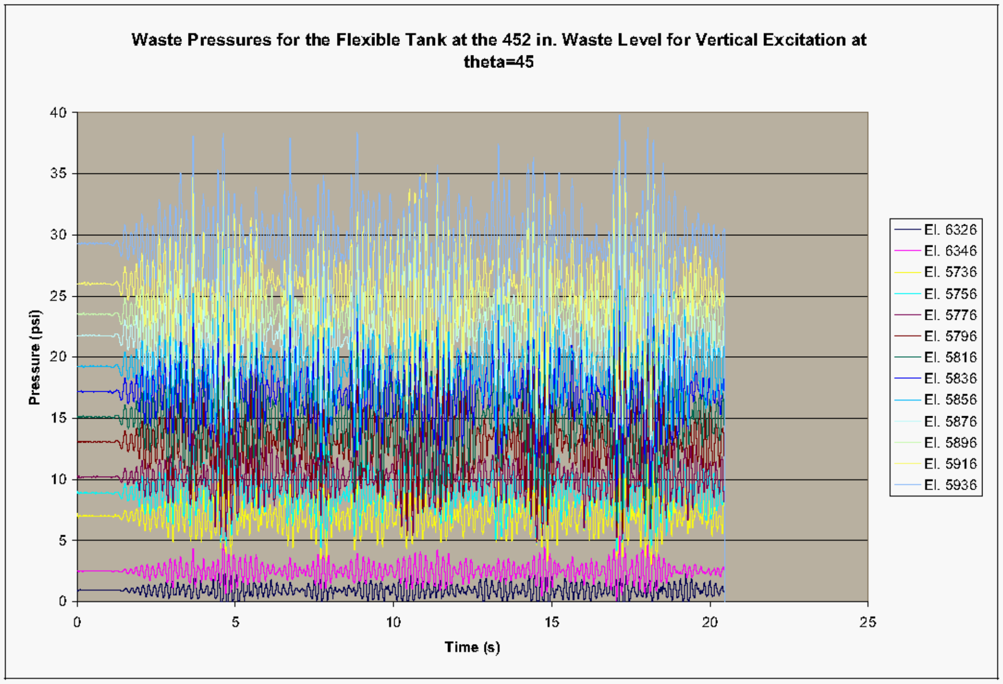


Figure 6-16. Waste Pressure Time Histories for the Flexible Tank at the 452 in. Waste Level for Vertical Excitation at θ=90°.

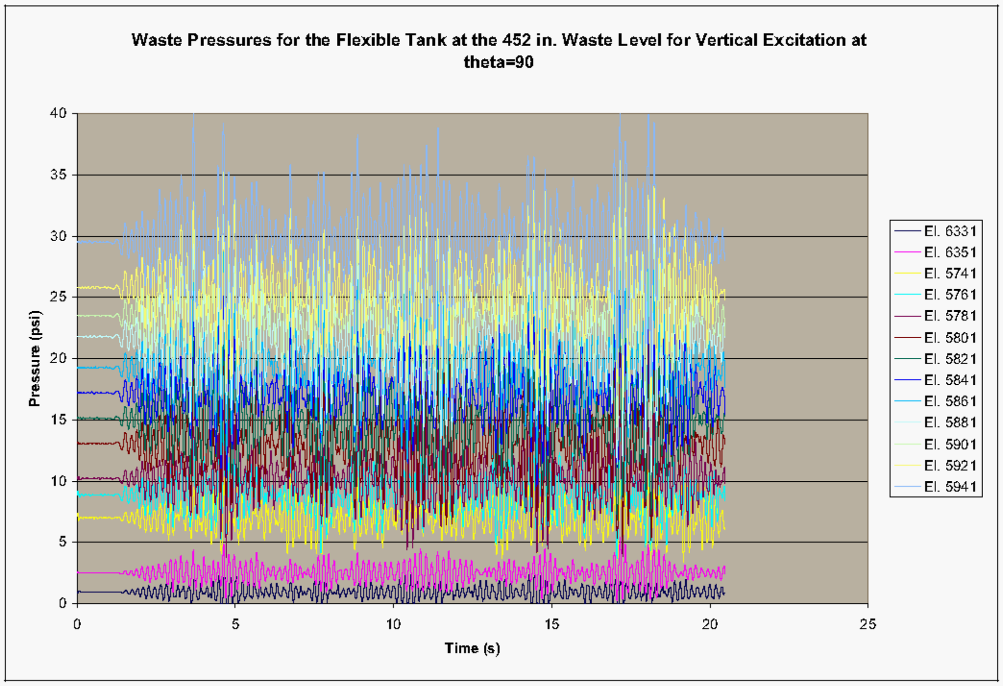


Figure 6-17. Pressure Time History for Bottom Center Contact Element 5971 for 452 in. Waste Level and Vertical Excitation.

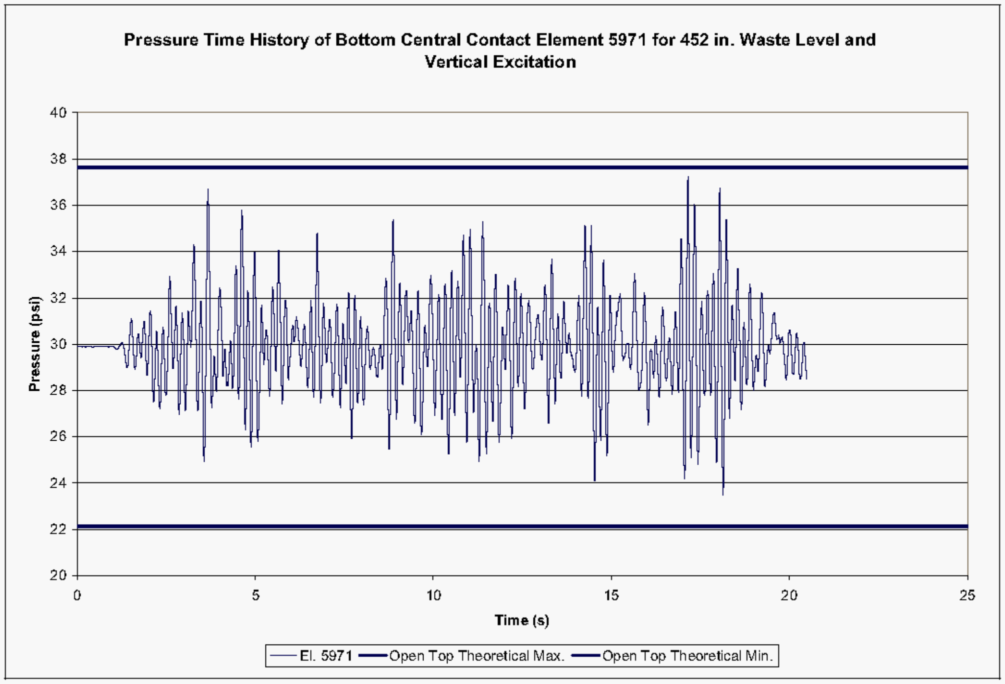
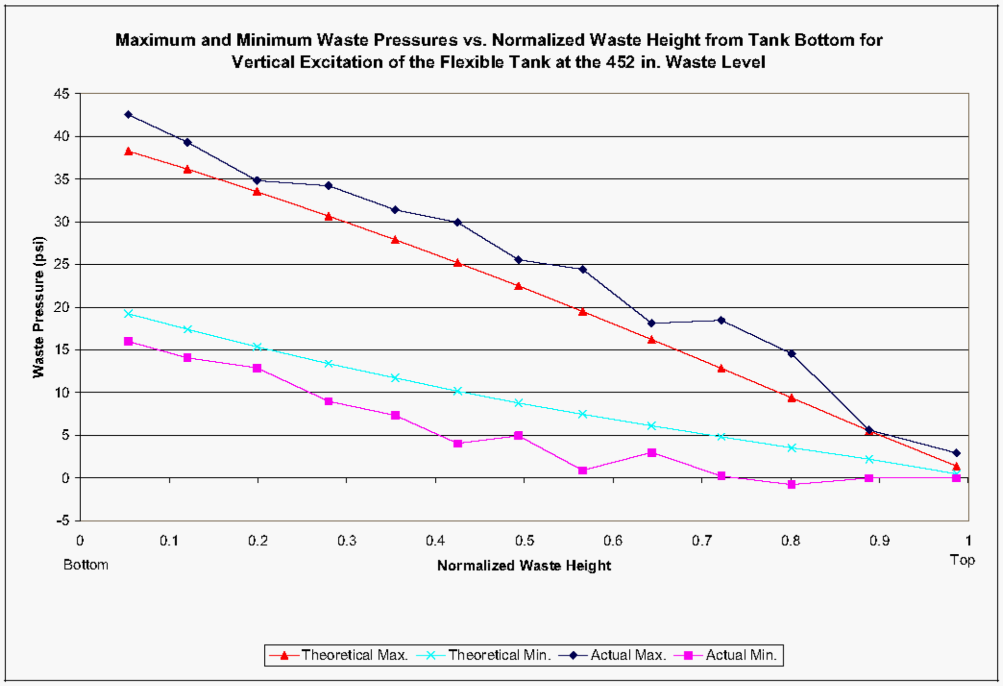


Figure 6-18. Maximum and Minimum Waste Pressures vs. Normalized Waste Height from Tank Bottom for the 452 in. Waste Level and Vertical Excitation.



6.3 MAXIMUM SLOSH HEIGHT RESULTS

The maximum slosh height according to the theory for the open top tank is 24.5 in. while the maximum slosh height from the simulation for the rigid case is approximately 8 in., or 1/3 of the open top theoretical value (See Section 4.3). As was shown earlier, the ability to accurately predict slosh heights and the associated convective response is a limitation of the ANSYS model and therefore slosh heights were not evaluated for this case.

6.4 ELEMENT STRESSES

6.4.1 Horizontal Excitation Run

Mid-plane hoop stresses for the tank shell elements at θ=0, 45, and 90° are presented as Figure 6-19, Figure 6-20, and Figure 6-21, respectively. The general behavior of the hoop stresses is reasonable with the peak stresses generally increasing with waste depth, and decreasing with the angular distance from the plane of excitation in accordance with the waste pressures.

Figure 6-19. Mid-Plane Hoop Stress for the Flexible Tank at the 460 in. Waste Level at θ=0.

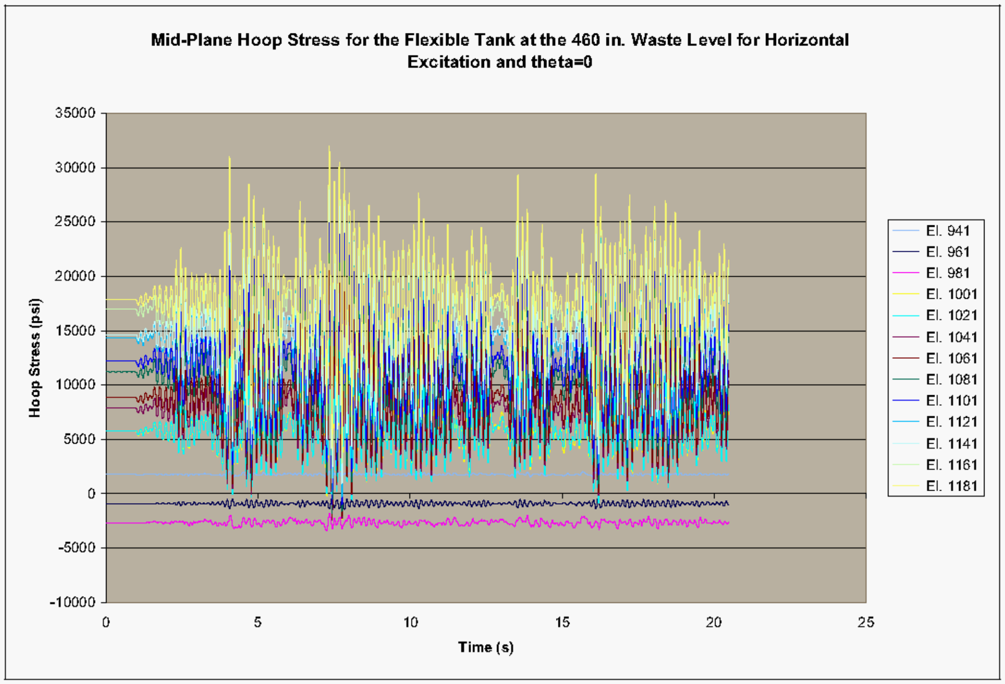


Figure 6-20. Mid-Plane Hoop Stress for the Flexible Tank at the 460 in. Waste Level at θ=45°.

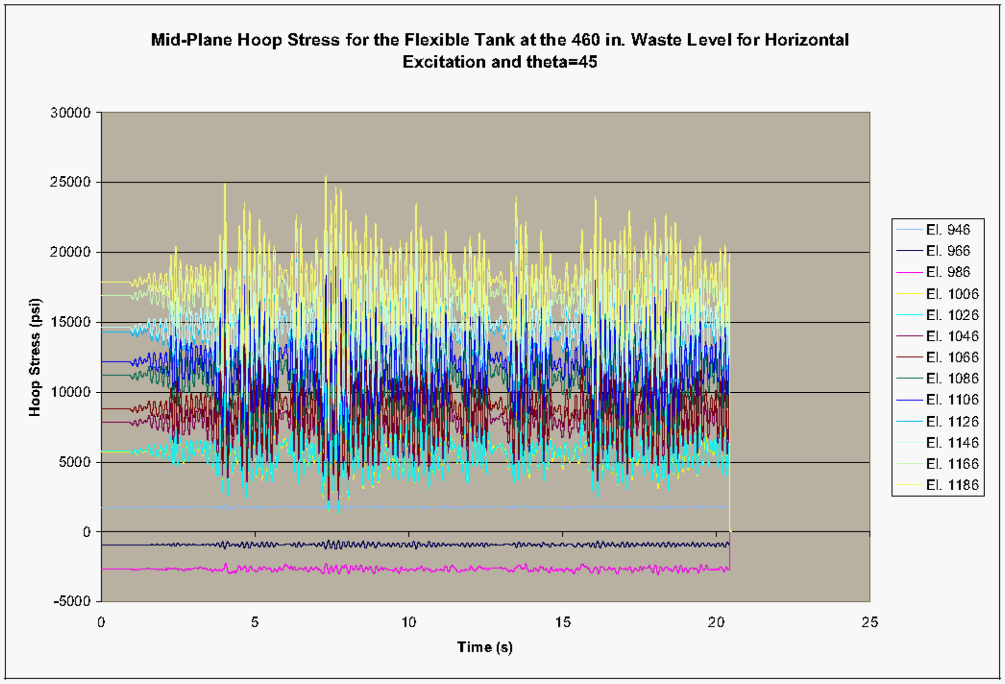
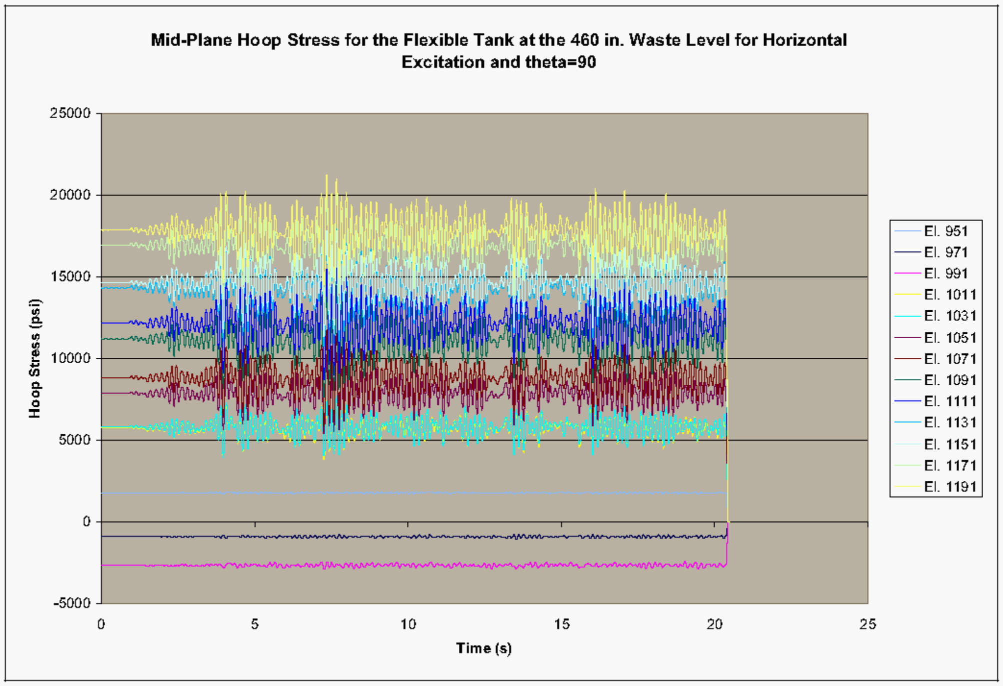


Figure 6-21. Mid-Plane Hoop Stress for the Flexible Tank at the 460 in. Waste Level at θ=90°.



7.0 ANSYS TO DYTRAN COMPARISONS

This report has presented the results of a series of ANSYS analyses of simplified primary tank models. A parallel study was conducted using the finite element code Dytran, and the results of that study are documented in the companion report Abatt (2006). The goal of the two studies was to evaluate the capabilities and limitations of each code for performing fluid-structure interaction analysis of a DST primary tank. Although the investigations are documented in separate reports, selected results are compared directly in the following sections.

As described earlier in this report, and in the companion report documenting the Dytran analyses, the two waste levels of interest are 422 in. and 460 in. The Dytran analyses were performed at these two waste levels. Due to modeling limitations, the lower waste level was modeled in ANSYS as 424 in. At the higher waste level, the ANSYS models were performed at 460 in. for horizontal runs and 452 in. for vertical runs. In the comparison plots to follow, the configurations are generically referred to as the 422 and 460 in. levels, but the actual waste levels used for the ANSYS analyses are as described above. Thus, slight inherent differences exist in some of the solutions due to the difference in waste levels. The theoretical values shown in the plots are for the intended waste levels of 422 and 460 in.

7.1 FREQUENCIES AND SLOSH HEIGHTS

A summary of fundamental frequencies and maximum slosh heights predicted by both ANSYS and Dytran appears as Table 7-1. Both ANSYS and Dytran predict fundamental frequencies that agree well with theory, although Dytran agrees slightly better with theoretical values of convective and breathing mode frequencies. It is clear that the ANSYS model is deficient in its ability to predict meaningful slosh heights.

Table 7-1. Comparison of Frequencies and Maximum Slosh Heights Predicted by ANSYS and Dytran.

Configuration	First Convective Mode Frequency (Hz)			Impulsive Mode Frequency (Hz)			Breathing Mode Frequency (Hz)			Maximum Slosh Height (in)		
	Theory	Dytran	ANSYS	Theory	Dytran	ANSYS	Theory	Dytran	ANSYS	Theory	Dytran	ANSYS
Rigid 422	0.19	0.19	0.184[2]	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	23.7	25.4	8
Rigid 460[1]	0.2	0.2	0.192	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	24.5	21.1	8
Flexible 422	0.19	0.19	0.184[3]	7.0	6.85	7.5[2]	6.1	6.0	6.6[2]	23.7	24.5	8
Flexible 460[1]	0.2	0.2	0.192[3]	6.5	6.4	6.6[4]	5.5	5.5	5.7[4]	24.5	20.1	8

[1]Theoretical solutions for the 460 in. waste level are based on an open tank with vertical walls and a hinged top boundary condition.
[2]Based on 424 in. waste level
[3]Convective frequency response based on rigid tank.
[4]Based on 452 in. waste level.

7.2 HYDRODYNAMIC FORCES

Comparisons between the overall reaction forces predicted by ANSYS and Dytran for the flexible tank models are presented in this section. In order to match the Dytran data to the ANSYS data, time scales were shifted as appropriate and the Dytran data was reversed in sign. The correct signs for the reactions are those predicted by Dytran since the ANSYS data was a result of nodal force post-processing. The results are presented for comparison, but if a physical interpretation of the reaction force is desired, the signs should be reversed from those shown in the plots. For example, in Figure 7-4, the static portion of the vertical reaction force is a downward force due to gravity, and the peak dynamic component of the reaction force occurs in the same direction as the waste weight.

A comparison of the overall horizontal reaction force due to horizontal seismic excitation for the flexible tank at the 422 in. waste level is shown in Figure 7-1. The general agreement between the two responses is good with the peak reaction force predicted by ANSYS slightly higher (that is, conservative) relative to that predicted by Dytran. The comparison of vertical responses to vertical input shown in Figure 7-2 also shows similar responses, and again, the peak response from ANSYS is slightly conservative relative the Dytran prediction.

A comparison of the total horizontal reaction force for horizontal seismic excitation of the flexible tank at the 460 in. waste level is shown as Figure 7-3. Once again, the responses are very similar and the peak reaction force predicted by ANSYS is slightly greater than the peak reaction force predicted by Dytran. Figure 7-4 shows the comparison of the total vertical reaction forces for vertical seismic input for the flexible tank at the 460 in. waste level. This time, although the responses are similar, the higher peak response is predicted by Dytran rather than ANSYS. A review of Figure 7-4 also shows that both models predict higher peak force than would be expected from the corresponding open top theoretical solution.

Comparison of the reaction forces from the ANSYS and Dytran models shows that the responses from the models are similar with ANSYS generally being conservative relative to Dytran. Both models predict responses that are in good agreement with theoretical solutions. In terms of global reactions on the primary tank, both ANSYS and Dytran appear capable of providing good results. In particular, since the loads into the j-bolts connecting the primary tank to the concrete dome are driven by the overall forces on the primary tank, it appears that a global ANSYS model is sufficient for analysis of the j-bolts and that any sub-model of the primary tank need not contain the j-bolts.

Figure 7-1. Comparison of ANSYS and Dytran Total Horizontal Reaction Forces for the Flexible Tank at the 422 in. Waste Level Under Horizontal Seismic Excitation.

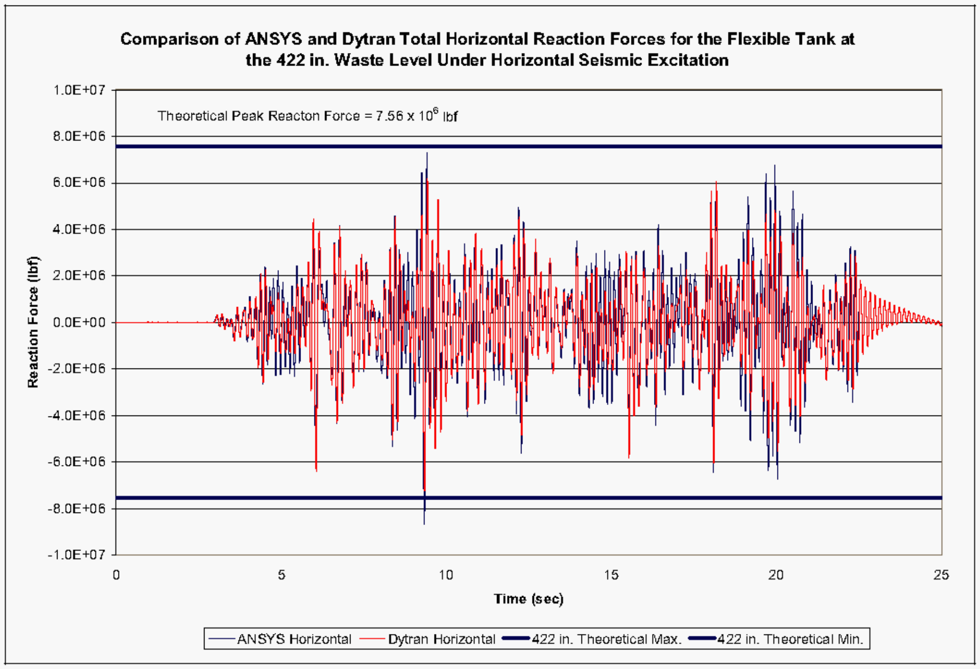


Figure 7-2. Comparison of ANSYS and Dytran Total Vertical Reaction Forces for the Flexible Tank at the 422 in. Waste Level Under Vertical Seismic Excitation.

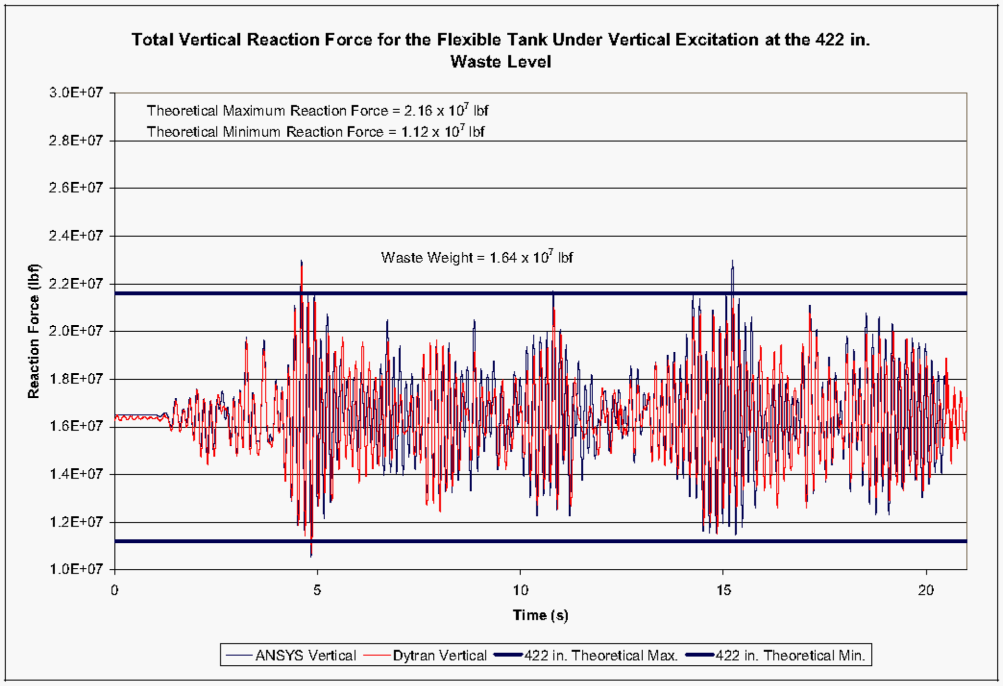


Figure 7-3. Comparison of ANSYS and Dytran Total Horizontal Reaction Forces for the Flexible Tank at the 460 in. Waste Level Under Horizontal Seismic Excitation.

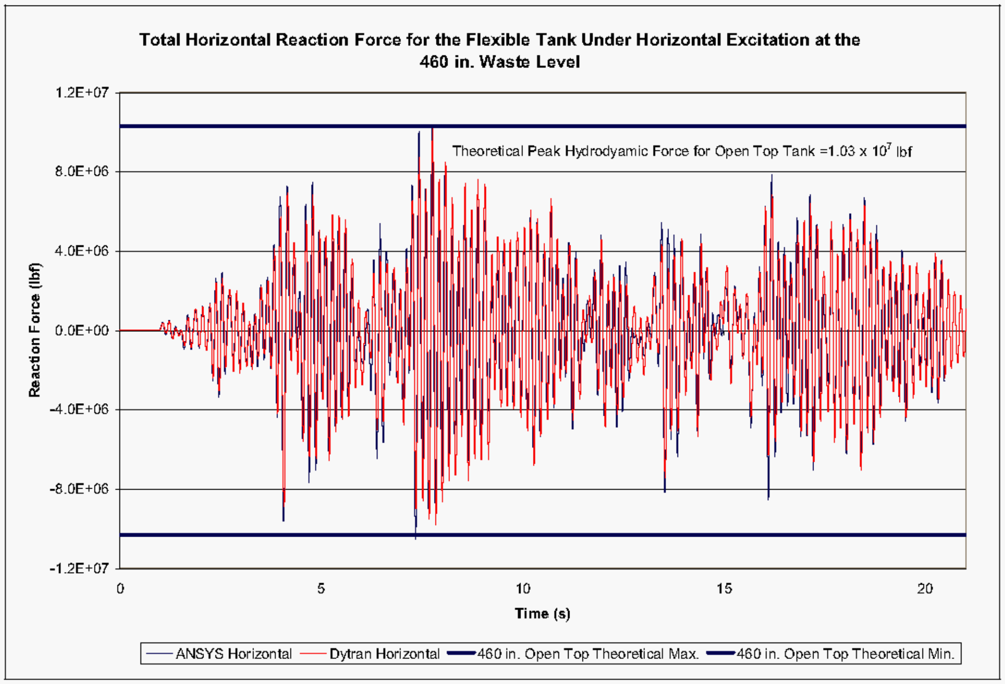
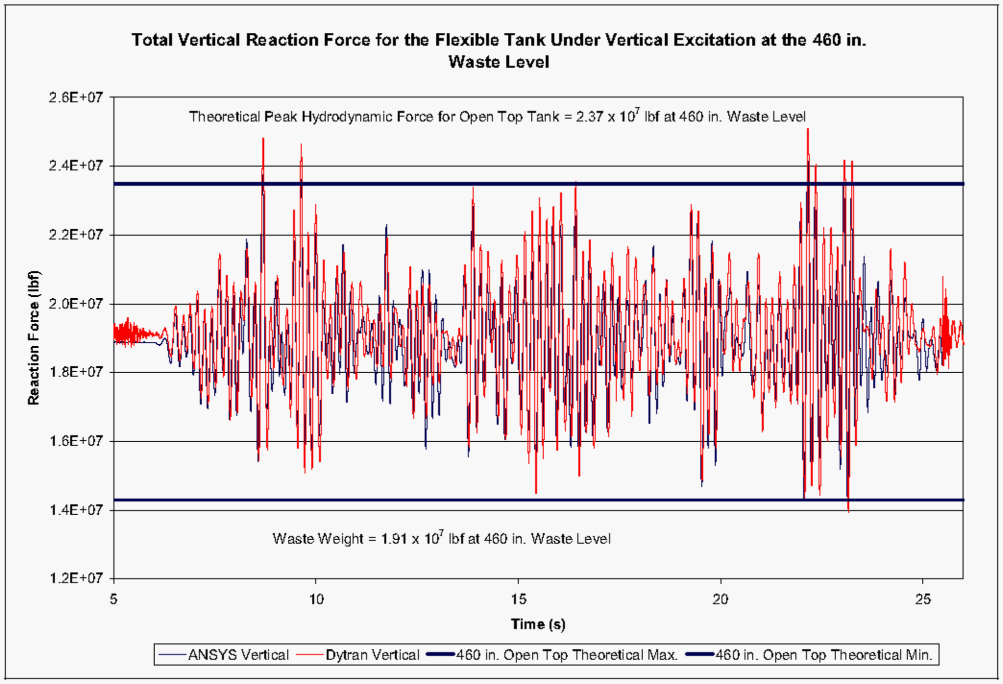


Figure 7-4. Comparison of ANSYS and Dytran Total Vertical Reaction Forces for the Flexible Tank at the 460 in. Waste Level Under Vertical Seismic Excitation.



7.3 WASTE PRESSURES

Direct comparisons of waste pressures predicted by ANSYS and Dytran are presented in this section. To be consistent with the pressures reported by ANSYS, the Dytran pressures have been shifted down by 14.7 lbf/in^2, since the ANSYS simulations were run at gage pressure and the Dytran simulations were performed at absolute pressure. The ANSYS and Dytran model meshes were not identical, so comparisons are made for waste elements at similar elevations. All comparisons were made for elements along the plane of excitation (θ=0). The waste element numbers, centroidal elevations, and theoretical hydrostatic pressures (calculated via $p=p_0+\rho gh$) are summarized in Table 7-2. The element numbers for ANSYS are actually contact element numbers between the waste and the primary tank, since these are the elements used to report the waste pressures from ANSYS.

Waste element pressures for the 422 in. waste level are presented as Figure 7-5 and Figure 7-6. A comparison of waste pressures near the top and bottom of the tank is shown in Figure 7-5, and a comparison of waste pressures approximately 2/3 the way up the waste is shown in Figure 7-6. Both plots show reasonably good agreement with the dynamic pressures reported by ANSYS tending to run slightly higher than those from Dytran except at a few isolated peaks near the waste surface in Figure 7-5. The plots also show that in the upper portion of the waste, the low-frequency convective response is more pronounced in ANSYS than in Dytran.

Wastes pressures from the simulations at the 460 in. waste level are shown in Figure 7-7 and Figure 7-8. The responses are again similar, but at the bottom of the waste, the peak pressures reported by Dytran exceed those reported by ANSYS. In the upper portion of the waste, the peak pressures from ANSYS are greater than the peak pressures from Dytran. The convective response is also less apparent in the ANSYS simulation at the 460 in. waste level than at the 422 in. waste level.

Table 7-2. Summary of Centroidal Elevations for ANSYS and Dytran Selected Waste Elements at θ=0.

ANSYS Element No.	Centroidal Elevation from Tank Bottom (in.)	Theoretical Hydrostatic Pressure (psi)	Dytran Element No.	Centroidal Elevation from Tank Bottom (in.)	Theoretical Hydrostatic Pressure (psi)*
422 in. Waste Level					
5521	401.9	1.4	9753	404.3	1.1
5581	291.8	8.1	7566	298.2	7.6
5721	54.5	22.7	2463	50.5	22.8
460 in. Waste Level					
5511	438.3	1.4	10482	441.0	1.3
5831	291.8	11.1	7566	298.2	10.7
5971	54.5	26.8	2463	50.5	27.1

*The theoretical waste pressures shown for Dytran have been shifted down by 14.7 lbf/in^2 to be consistent with the theoretical pressures shown for ANSYS.

Figure 7-5. Comparison of ANSYS and Dytran Waste Pressures for the Flexible Tank at the 422 in. Waste Level Under Horizontal Excitation – Waste Elements Near Tank Top and Bottom at θ=0.

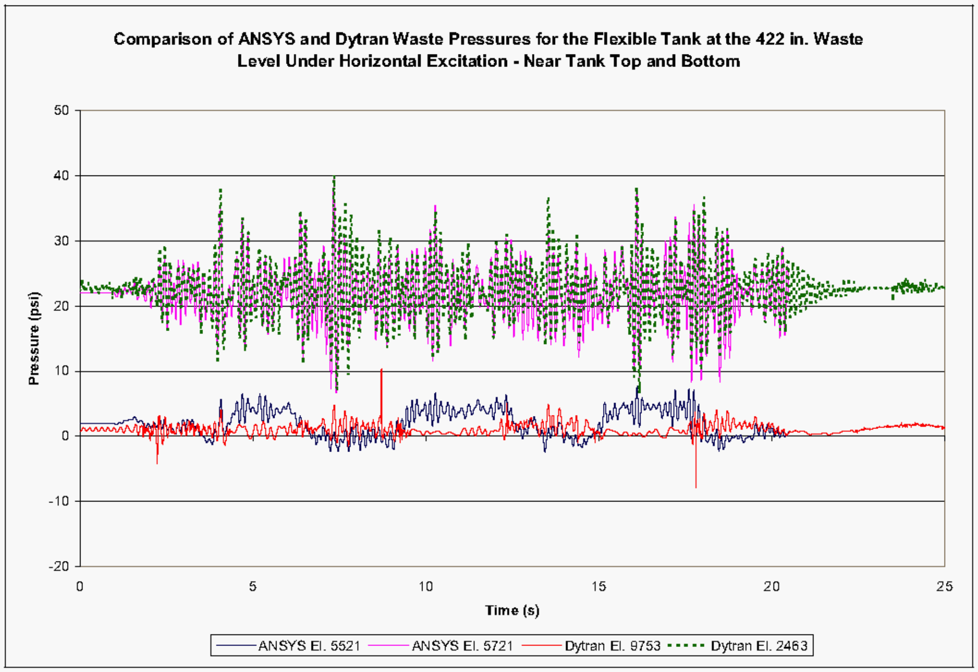


Figure 7-6. Comparison of ANSYS and Dytran Waste Pressures for the Flexible Tank at the 422 in. Waste Level Under Horizontal Excitation – Waste Elements at Elevation 292 in. Above Tank Bottom at θ=0.

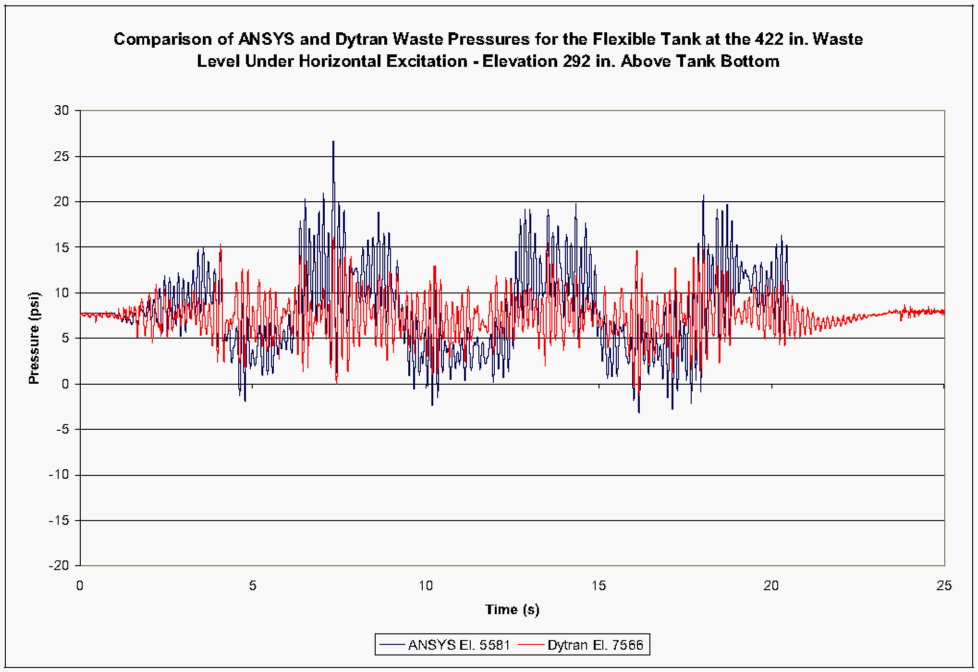


Figure 7-7. Comparison of ANSYS and Dytran Waste Pressures for the Flexible Tank at the 460 in. Waste Level Under Horizontal Excitation – Waste Elements Near Tank Top and Bottom at θ=0.

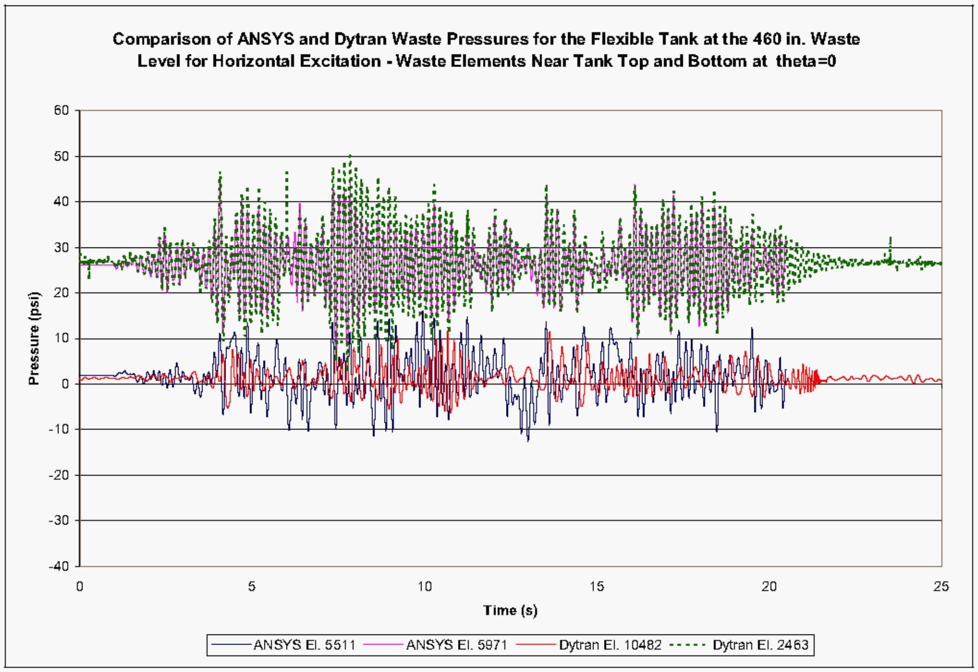
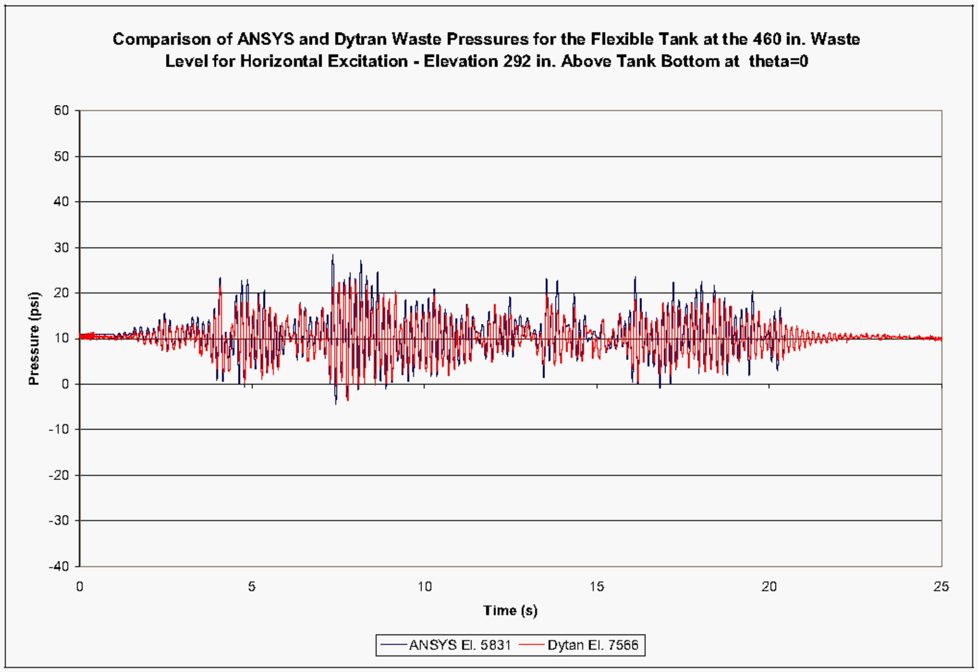


Figure 7-8. Comparison of ANSYS and Dytran Waste Pressures for the Flexible Tank at the 460 in. Waste Level Under Horizontal Excitation – Waste Elements at Elevation 292 in. Above Tank Bottom at θ=0.



7.4 ELEMENT STRESSES

Direct comparisons of element mid-wall hoop stresses predicted by ANSYS and Dytran are presented in this section. The ANSYS and Dytran model meshes were not identical, so comparisons are made for tank wall elements at elevations as close as possible. However, the difference in mesh resolutions and the local modeling of the tank knuckle region is expected to cause differences in the reported stresses even at similar elevations. All comparisons were made for elements along the plane of excitation (θ=0). The tank wall element numbers and centroidal elevations are summarized in Table 7-3.

Mid-wall hoop stresses at the 422 in. waste level are presented for tank elements near the waste free surface, approximately 2/3 of the way up from the tank bottom, and near the tank bottom in Figure 7-9, Figure 7-10, and Figure 7-11, respectively. The static portion of the hoop stresses shown in Figure 7-9 differ by approximately 1,000 lbf/in^2, even though the element elevations are nearly the same as shown in Table 7-3. According to Figure 7-5, the waste pressures adjacent to these elements are nearly the same, so apparently the difference in stresses is due to a combination of the difference in mesh resolution and the difference in how the two codes transmit the waste pressures into the structure. Interestingly, whereas the convective response was more pronounced in the waste pressures predicted by ANSYS at this elevation, the convective response is more apparent in the stresses predicted by Dytran. This may be due to the difference in the Lagrangian vs. Eulerian formulation of the waste elements.

At the 292 in. elevation, and at the bottom, the responses are similar with ANSYS predicting slightly higher stresses at the 292 in. level, and Dytran predicting slightly higher stresses near the tank bottom. The differences near the tank bottom may be due partly to the difference in the details of the mesh in the tank knuckle region and partly due to the more than nine inch difference in the elevation of the wall element centroids.

Table 7-3. Summary of Centroidal Elevations for ANSYS and Dytran Selected Tank Wall Elements at θ=0.

ANSYS Element No.	Centroidal Elevation from Tank Bottom (in.)	Dytran Element No.	Centroidal Elevation from Tank Bottom (in.)
961	438.3	399	441.8
981	401.9	406	402.9
1041	291.8	432	292.8
1181	54.5	447	63.9

Figure 7-9. Comparison of ANSYS and Dytran Mid-Plane Hoop Stress at Primary Tank Wall Element Near the Waste Free Surface for the Flexible Tank at the 422 in. Waste Level for Horizontal Excitation and θ=0.

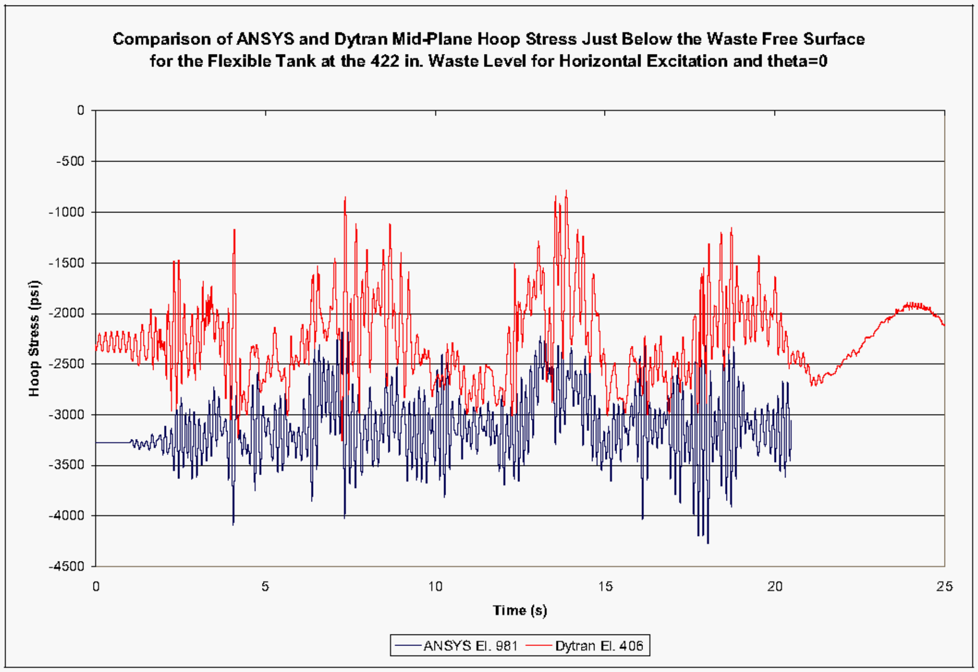


Figure 7-10. Comparison of ANSYS and Dytran Mid-Plane Hoop Stress at an Elevation of 292 in. from the Tank Bottom for the Flexible Tank at the 422 in. Waste Level for Horizontal Excitation and θ=0.

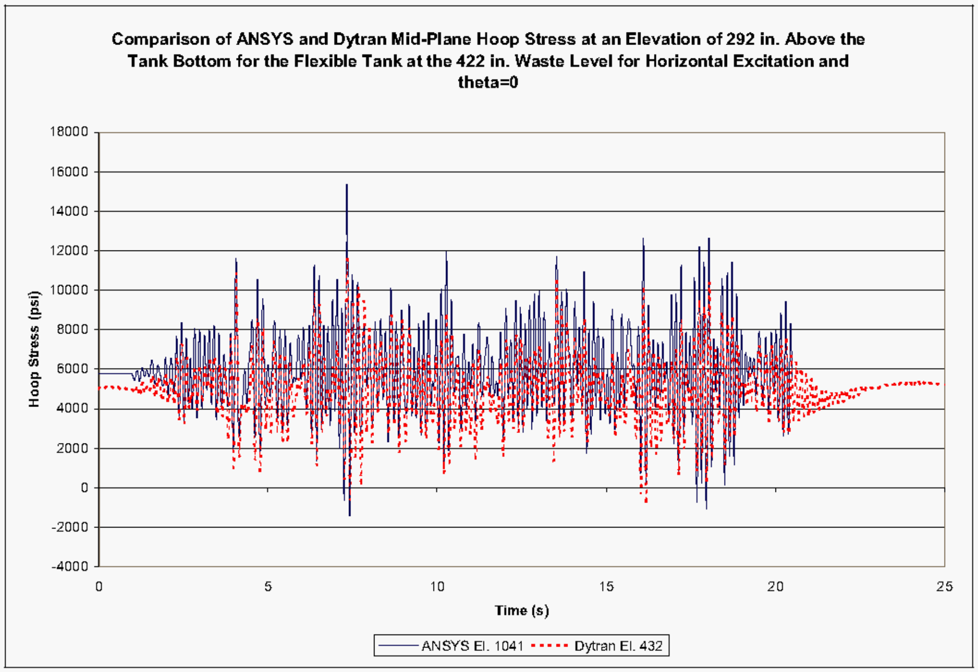


Figure 7-11. Comparison of ANSYS and Dytran Mid-Plane Hoop Stress at Primary Tank Wall Element Near the Tank Bottom for the Flexible Tank at the 422 in. Waste Level for Horizontal Excitation and θ=0.

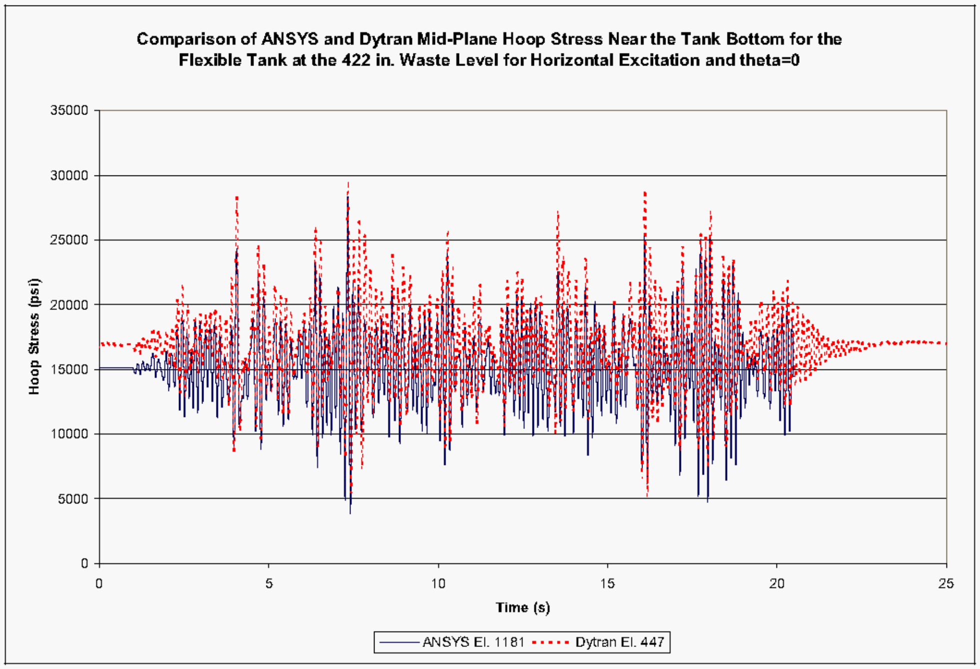


Figure 7-12. Comparison of ANSYS and Dytran Mid-Plane Hoop Stress at Primary Tank Wall Element Near the Waste Free Surface for the Flexible Tank at the 460 in. Waste Level for Horizontal Excitation and θ=0.

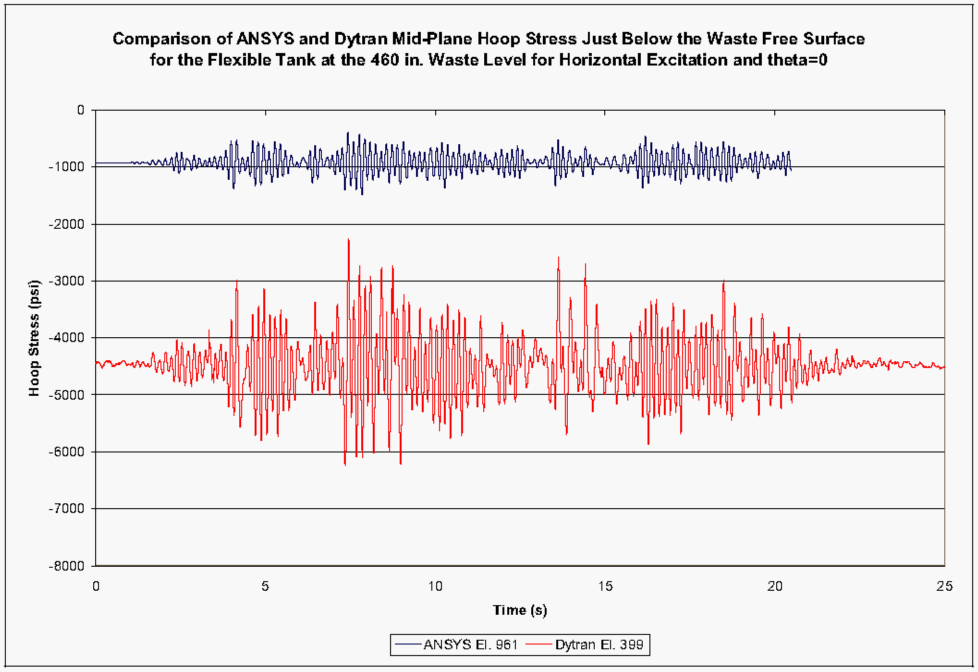


Figure 7-13. Comparison of ANSYS and Dytran Mid-Plane Hoop Stress at an Elevation of 292 in. from the Tank Bottom for the Flexible Tank at the 460 in. Waste Level for Horizontal Excitation and θ=0.

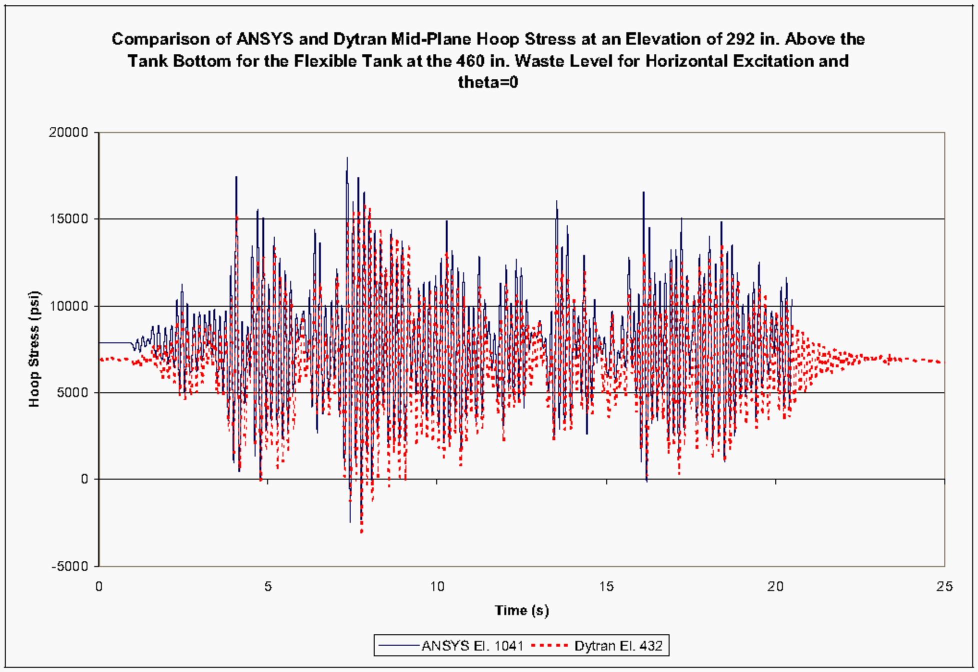
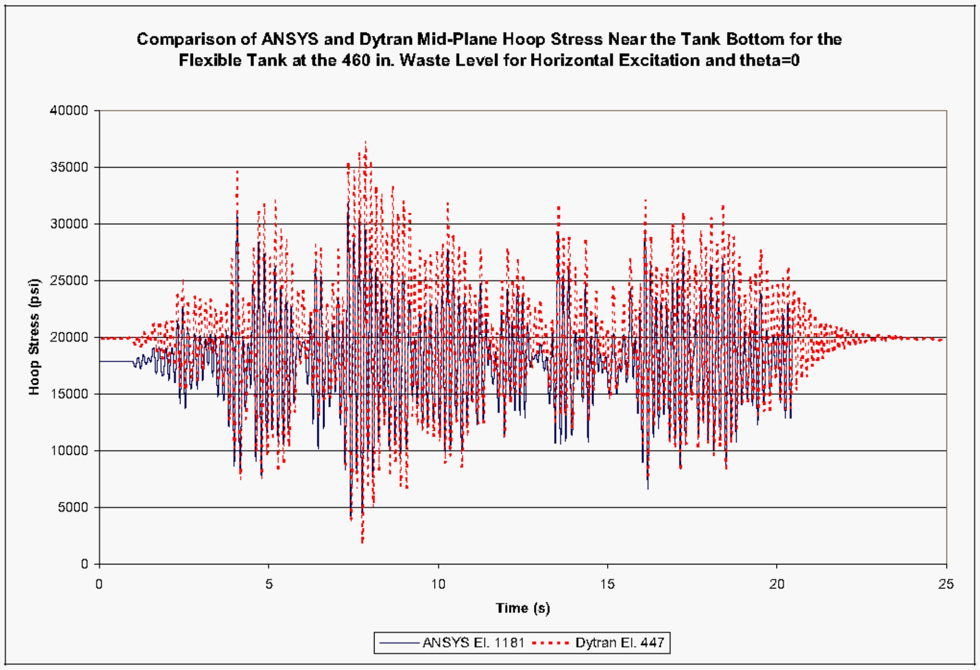


Figure 7-14. Comparison of ANSYS and Dytran Mid-Plane Hoop Stress at Primary Tank Wall Element Near the Tank Bottom for the Flexible Tank at the 460 in. Waste Level for Horizontal Excitation and θ=0.



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APPENDIX A

Description of Input and Results Files

ANSYS Input Files

File Name	Description
Run-Tank.txt	Calls each input for development of model
Tank-Coordinates-AP.txt	Defines key geometry and model parameters. Concrete geometry set to match PNNL section cut locations.
Tank-Props-Rigid.txt	Defines concrete material and real properties for model. Uses "Rigid" concrete properties. Each tank layer can be assigned unique properties
Tank-Mesh1.txt	Creates concrete tank mesh. Foundation and wall are separate entities
Primary-Props-XX-XXXX.txt	Defines primary tank material and real properties.
Primary.txt	Creates primary tank mesh. Primary tank is not connected to concrete tank.
Insulate.txt	Creates insulating concrete mesh. Uses existing geometry from concrete and primary tanks, but is not connected.
Waste-Solid-XX.txt	Creates model of waste. Uses Solid45 elements with low shear modulus. Uses primary tank geometry.
Interface.txt	Creates interface connections or contacts between pieces of model
Interface2.txt	Creates interface connections or contacts between pieces of model
Bolts-ns.txt	Creates elements for J-Bolts
Liner.txt	Creates elements for Secondary Liner
Near-Soil-1.txt	Creates soil model for excavated region around tank. Merges coincident nodes with concrete tank.
Soil-Props-Mean-Geo.txt	Defines all soil geometry and material properties. Excavated region and native soil can have different material properties.
Far-Soil.txt	Creates far-field/native soil to a radius of 320 ft and depth of 266 ft. Merges coincident nodes with near soil and concrete tank. Places large mass at bottom of model for excitation force.
Slave.txt	Creates slaved boundary conditions around exterior of model.
Boundary.txt	Creates boundary conditions for symmetry. Does not set boundary conditions for solution phase.
Waste-Contact.txt	Extracts Contact data for Waste/Primary Tank contact elements
Live_Load.txt	Applies surface concentrated load over center of dome
Outer-Spar.txt	Creates spar elements at edge of soil model to control shear behavior.
Slosh-TH.txt	Extracts portion of model to be used in sloshing study and applies appropriate boundary conditions
Solve-Slosh.txt	Performs time history solution
Stress-Primary.txt Stress-compb.txt Stress-compm.txt Stress-compt.txt	Extracts primary tank stresses for the bottom, middle, and top surfaces of shell elements.
Waste-Reaction.txt	Extracts total waste reaction for full time history
Waste-Surface-XX.txt	Extracts surface displacement over time history

Results Files

File Name	Description
Stress-pt_#max-b.out Stress-pt_#max-m.out Stress-pt_#max-t.out	Listing of Minimum and Maximum stress components for primary tank. # indicates slice angle, b, m, and t, indicate bottom, middle, and top surfaces respectively. Used for flexible tank runs only.
Stress-pt_#th -b.out Stress-pt_#th -m.out Stress-pt_#th -t.out	Listing of full time history for stress components for primary tank. # indicates slice angle, b, m, and t, indicate bottom, middle, and top surfaces respectively. Used for flexible tank runs only
Waste-Cont_#max.out	Listing of minimum and maximum waste contact element data. # indicates slice angle
Waste-Cont_#th.out	Listing of full time history for waste contact element data. # indicates slice angle
Waste-Surf_#max.out	Listing of minimum and maximum waste surface vertical displacement data. # indicates slice angle
Waste-Surf_#th.out	Listing of full time history for waste surface vertical displacement data. # indicates slice angle
Waste-Reaction.out	Listing of total waste contact force (horizontal and vertical) for full time history.

Post-Processing Files

File Name	Description
Flex-## Total Reaction.xls	Excel spreadsheet containing results from a given run for the total reaction (Waste-Reaction.out).
Flex-##-TH-Max.xls	Excel spreadsheet containing results from a given run for the maximum waste contact element pressures (Waste-Cont_#max.out)
Flex-##-Disp-TH-Max.xls	Excel spreadsheet containing results from a given run for the maximum waste surface vertical displacement (Waste-Surf_#max.out)
Flex-##-Seismic Stress Comp Summary.xls	Excel spreadsheet containing results from a given run for the stress results for the primary tank (Stress-pt_#max-b.out, Stress-pt_#max-m.out, Stress-pt_#max-t.out)
*.xls	Other excel spreadsheets summarize various results for the sloshing analysis or are used as in intermediate step in developing the spreadsheets listed above.

APPENDIX B

Theoretical Solutions

(61 pages including cover sheet)

Prepared by: F. G. Abatt
M&D Professional Services
10/24/05
Rev. 2

Theoretical Fluid Response
Calculations for Rigid Primary Tank
at 424 in. Waste Level
ANSYS Model Configuration

Checked by: B.G. Carpenter
M&D Professional Services
2/1/06

$H_l := 424 \cdot in$ Baseline waste level as modeled in ANSYS

$H_t := 460 \cdot in$ Height to primary tank tangent line

$\frac{H_l}{H_t} = 0.92$ Ratio of waste height to tank height

$g := 386.4 \cdot \frac{in}{sec^2}$

$R := 450 \cdot in$ Tank radius

$\frac{H_l}{R} = 0.94$ Ratio of waste height to tank radius

$i := 0..2$

$\lambda := \begin{pmatrix} 1.841 \\ 5.331 \\ 8.536 \end{pmatrix}$ Bessel function roots

$\theta := \begin{pmatrix} 0 \cdot deg \\ 45 \cdot deg \\ 90 \cdot deg \end{pmatrix}$ Circumferential location of waste elements for which pressures are reported

Convective Frequencies

$fcon_i := \frac{1}{2 \cdot \pi} \cdot \left[\sqrt{\left[\lambda_i \left[\frac{g}{R} \cdot \tanh \left[\lambda_i \cdot \left(\frac{H_l}{R} \right) \right] \right] \right]} \right]$ Eqn. 4.14 of BNL 1995

$fcon = \begin{pmatrix} 0.19 \\ 0.34 \\ 0.43 \end{pmatrix} Hz$ First three convective frequencies

$\rho_l := 1.59 \cdot 10^{-4} \cdot \frac{lbf \cdot sec^2}{in^4}$ waste density - specific gravity = 1.7

Determine Convective Pressures on the Tank Wall:

$$z := \begin{pmatrix} 24.5\cdot in \\ 54.5\cdot in \\ 90.0\cdot in \\ 126.4\cdot in \\ 160.25\cdot in \\ 191.15\cdot in \\ 222.05\cdot in \\ 255.75\cdot in \\ 291.75\cdot in \\ 327.25\cdot in \\ 362.25\cdot in \\ 401.9\cdot in \end{pmatrix}$$

Vertical location of element centroids at which pressures are reported.

$$\eta_l := \frac{z}{H_l}$$

Ratio of tank wall vertical location to waste height for waste element centroids.

$\eta_l =$

	0
0	0.06
1	0.13
2	0.21
3	0.3
4	0.38
5	0.45
6	0.52
7	0.6
8	0.69
9	0.77
10	0.85
11	0.95

Determine convective coefficients as a function of dimensionless height per Eqn. 4.4 BNL 1995

$$con_0(\eta_l) := \left[\frac{2}{(\lambda_0)^2 - 1} \cdot \frac{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$con_1(\eta_l) := \left[\frac{2}{(\lambda_1)^2 - 1} \cdot \frac{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$con_2(\eta_l) := \left[\frac{2}{(\lambda_2)^2 - 1} \cdot \frac{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$con_0(\eta_l) =$

	0
0	0.29
1	0.29
2	0.31
3	0.33
4	0.35
5	0.38
6	0.41
7	0.46
8	0.52
9	0.58
10	0.66
11	0.77

$con_1(\eta_l) =$

	0
0	$1\cdot10^{-3}$
1	$1.17\cdot10^{-3}$
2	$1.56\cdot10^{-3}$
3	$2.25\cdot10^{-3}$
4	$3.28\cdot10^{-3}$
5	$4.67\cdot10^{-3}$
6	$6.7\cdot10^{-3}$
7	$9.96\cdot10^{-3}$
8	0.02
9	0.02
10	0.04
11	0.06

$con_2(\eta_l) =$

	0
0	$1.99\cdot10^{-5}$
1	$2.83\cdot10^{-5}$
2	$5.09\cdot10^{-5}$
3	$9.92\cdot10^{-5}$
4	$1.87\cdot10^{-4}$
5	$3.36\cdot10^{-4}$
6	$6.04\cdot10^{-4}$
7	$1.14\cdot10^{-3}$
8	$2.26\cdot10^{-3}$
9	$4.44\cdot10^{-3}$
10	$8.63\cdot10^{-3}$
11	0.02

Impulsive pressure coefficient as a function of dimensionless wall height

$c_i(\eta_l) := 1 - con_0(\eta_l) - con_1(\eta_l) - con_2(\eta_l)$ Eqn. 4.7 BNL 1995

$c_i(\eta_l) =$

	0
0	0.71
1	0.71
2	0.69
3	0.67
4	0.65
5	0.62
6	0.58
7	0.53
8	0.47
9	0.39
10	0.29
11	0.16

Calculate maximum values of dynamic wall pressures from spectral acceleration of dome input TH.

Consider the first three convective mode spectral accelerations for the 0.5% damped spectrum

$SA_{c0} := 0.062 \cdot g$ $SA_{c0} = 23.96 \frac{in}{sec^2}$ Figure 2-24 of main report

$SA_{c1} := 0.108 \cdot g$ $SA_{c1} = 41.73 \frac{in}{sec^2}$

$SA_{c2} := 0.163 \cdot g$ $SA_{c2} = 62.98 \frac{in}{sec^2}$

Associate the impulsive mode with the ZPA, since the tank is rigid.

$PGA := 0.276 \cdot g$ $PGA = 106.65 \frac{in}{sec^2}$ ANSYS dome RS from Spectr - Figure 2-22 of main report.

$$p_{maxconv}(\eta_1,\theta) := \left[\sqrt{\left(con_0(\eta_1)\cdot SA_{c0}\right)^2 + \left(con_1(\eta_1)\cdot SA_{c1}\right)^2 + \left(con_2(\eta_1)\cdot SA_{c2}\right)^2}\right]\cdot\left(\rho_l\cdot R\cdot\cos(\theta\cdot deg)\right)$$

$$p_{maximpulsive}(\eta_1,\theta) := \left[\sqrt{\left[c_i(\eta_1)\cdot(PGA)\right]^2}\right]\cdot\left(\rho_l\cdot R\cdot\cos(\theta\cdot deg)\right)$$

$$p_{max}(\eta_1,\theta) := \left[\sqrt{\left[\left(c_i(\eta_1)\right)\cdot(PGA)\right]^2 + \left(con_0(\eta_1)\cdot SA_{c0}\right)^2 + \left(con_1(\eta_1)\cdot SA_{c1}\right)^2 + \left(con_2(\eta_1)\cdot SA_{c2}\right)^2}\right]\cdot\left(\rho_l\cdot R\cdot\cos(\theta\cdot deg)\right)$$

Eqn. 4.24 BNL 1995

$p_{maximpulsive}(\eta_1, 0) =$ (units: $\frac{lbf}{in^2}$)

	0
0	5.43
1	5.38
2	5.28
3	5.13
4	4.93
5	4.7
6	4.42
7	4.05
8	3.56
9	2.96
10	2.24
11	1.19

Maximum impulsive dynamic pressures at theta = 0.

$p_{maxconv}(\eta_1, 0) =$ (units: $\frac{lbf}{in^2}$)

	0
0	0.49
1	0.5
2	0.52
3	0.56
4	0.6
5	0.65
6	0.71
7	0.79
8	0.89
9	1
10	1.14
11	1.33

Maximum convective dynamic pressures at theta = 0.

$p_{max}(\eta_1, 0) =$ (in $\frac{lbf}{in^2}$)

	0
0	5.45
1	5.4
2	5.31
3	5.16
4	4.97
5	4.75
6	4.48
7	4.13
8	3.67
9	3.13
10	2.51
11	1.79

Maximum total dynamic pressure at theta = 0.

$p_{max}(\eta_1, 45) =$ (in $\frac{lbf}{in^2}$)

	0
0	3.85
1	3.82
2	3.75
3	3.65
4	3.51
5	3.36
6	3.17
7	2.92
8	2.59
9	2.21
10	1.78
11	1.26

Maximum total dynamic pressure at theta = 45 degrees.

$p_{max}(\eta_1, 90) =$ (in $\frac{lbf}{in^2}$)

	0
0	0
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0

Maximum total dynamic pressure at theta = 90 degrees.

Calculate Maximum Slosh Height:

$$conmax := \begin{pmatrix} 0.837 \\ 0.073 \\ 0.028 \end{pmatrix}$$ Maximum value of convective coefficients at η_l=1

$$h_{maxslosh} := R \cdot \sqrt{\left(conmax_0 \cdot \frac{SA_{c0}}{g}\right)^2 + \left(conmax_1 \cdot \frac{SA_{c1}}{g}\right)^2 + \left(conmax_2 \cdot \frac{SA_{c2}}{g}\right)^2}$$ Eqn. 4.60 BNL 1995

$h_{maxslosh} = 23.71\,in$ Maximum theoretical slosh height

Calculate Maximum Total Hydrodynamic Force:

The maximum hydrodynamic force induced on the tank wall is given by Eqn. 4.31 of BNL 1995 with the instantaneous accelerations replaced by the maximum spectral accelerations. First determine the effective impulsive and convective masses.

$m_{lapprox} := \pi \cdot R^2 \cdot H_l \cdot \rho_l$ $m_{lapprox} = 4.29 \times 10^4 \frac{lbf \cdot sec^2}{in}$ Total waste mass based on circular cylinder approximation.

$m_l := 4.27 \cdot 10^4 \cdot \frac{lbf \cdot sec^2}{in}$ Actual waste mass reported by ANSYS model.

$$m_{c0} := \left[\frac{2}{\lambda_0 \cdot \left[\left(\lambda_0\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$

$m_{c0} = 1.94 \times 10^4 \frac{lbf \cdot sec^2}{in}$ First mode convective mass

$$m_{c1} := \left[\frac{2}{\lambda_1 \cdot \left[\left(\lambda_1\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$ Second mode convective mass

$$m_{c1} = 620.01\,\frac{\text{lbf}\cdot\text{sec}^2}{\text{in}}$$

$$m_{c2} := \left[\frac{2}{\lambda_2\cdot\left[\left(\lambda_2\right)^2 - 1\right]\cdot\left(\frac{H_l}{R}\right)}\right]\cdot\tanh\left[\lambda_2\cdot\left(\frac{H_l}{R}\right)\right]\cdot m_l$$

Third mode convective mass

$$m_{c2} = 147.76\,\frac{\text{lbf}\cdot\text{sec}^2}{\text{in}}$$

$$m_i := m_l - \left(m_{c0} + m_{c1} + m_{c2}\right)$$

Impulsive mass

$$m_i = 2.26\times 10^4\,\frac{\text{lbf}\cdot\text{sec}^2}{\text{in}}$$

$$F_{max} := m_i\cdot PGA + m_{c0}\cdot SA_{c0} + m_{c1}\cdot SA_{c1} + m_{c2}\cdot SA_{c2}$$

Eqn. 4.31 BNL 1995

$$F_{max} = 2.91\times 10^6\,\text{lbf}$$

Conservative estimate of maximum hydrodynamic force

The above expression is a conservative estimate because it assumes that the peak impulsive and convective forces occur simultaneously. A less conservative estimate can be made via a square-root-sum-of-the-squares (SRSS) combination.

$$F_{srss} := \sqrt{\left(m_i\cdot PGA\right)^2 + \left(m_{c0}\cdot SA_{c0}\right)^2 + \left(m_{c1}\cdot SA_{c1}\right)^2 + \left(m_{c2}\cdot SA_{c2}\right)^2}$$

Eqn. 4.31 BNL 1995 - SRSS

$$F_{srss} = 2.45\times 10^6\,\text{lbf}$$

SRSS estimate of peak hydrodynamic force

$$F_{conmax} := \sqrt{\left(m_{c0}\cdot SA_{c0}\right)^2 + \left(m_{c1}\cdot SA_{c1}\right)^2 + \left(m_{c2}\cdot SA_{c2}\right)^2}$$

$$F_{conmax} = 4.65\times 10^5\,\text{lbf}$$

Peak hydrodynamic force due to convective response - shows up in free oscillations.

Consider Vertical Excitation:

For a rigid tank, the period of the breathing mode is zero and the associated spectral acceleration is the vertical ZPA.

$ZPA_{vert} := 0.12 \cdot g$ ANSYS Haunch RS from Spectr - see also Figure 2-19 of main report.

The maximum wall pressure as a function of the dimensionless vertical distance is given by

$$p_{maxv}(\eta_l) := (0.8) \cdot \left(\cos\left(\frac{\pi}{2} \cdot \eta_l\right)\right) \cdot \left(\rho_l \cdot H_l \cdot ZPA_{vert}\right)$$ Eqn. 4.52 BNL 1995

$p_{maxv}(\eta_l) =$ $\frac{lbf}{in^2}$

	0
0	2.49
1	2.45
2	2.36
3	2.23
4	2.07
5	1.9
6	1.7
7	1.46
8	1.18
9	0.88
10	0.57
11	0.2

The maximum base pressure and force are given by

$p_{maxbasevert} := \rho_l \cdot H_l \cdot ZPA_{vert}$ $p_{maxbasevert} = 3.13 \frac{lbf}{in^2}$ Eqn. 4.55 BNL 1995

$F_{maxbasevert} := m_l \cdot ZPA_{vert}$ $F_{maxbasevert} = 1.98 \times 10^6 \, lbf$ Eqn. 4.57 BNL 1995

Reference:

BNL 1995, *Seismic Design and Evaluation Guidelines for the Department of Energy High-Level Waste Storage Tanks and Appurtenances*, BNL 52361, Rev. 10/95, Brookhaven National Laboratory, Upton, New York.

Prepared by: F. G. Abatt
M&D Professional Services
10/06/05
Rev. 1

Theoretical Fluid Response
Calculations for Rigid Primary Tank
at 452 in. Waste Level
ANSYS Model Configuration

Checked by: B.G. Carpenter
M&D Professional Services
2/1/06

$H_l := 452.0 \cdot in$ Baseline waste level

$H_t := 460.0 \cdot in$ Height to primary tank tangent line

$\frac{H_l}{H_t} = 0.98$ Ratio of waste height to tank height

$g := 386.4 \cdot \frac{in}{sec^2}$

$R := 450 \cdot in$ Tank radius

$\frac{H_l}{R} = 1$ Ratio of waste height to tank radius

$i := 0..2$

$\lambda := \begin{pmatrix} 1.841 \\ 5.331 \\ 8.536 \end{pmatrix}$ Bessel function roots

$\theta := \begin{pmatrix} 0 \cdot deg \\ 45 \cdot deg \\ 90 \cdot deg \end{pmatrix}$ Circumferential location of waste elements for which pressures are reported

Convective Frequencies

$fcon_i := \frac{1}{2 \cdot \pi} \cdot \left[\sqrt{\lambda_i \left[\frac{g}{R} \cdot \tanh\left[\lambda_i \cdot \left(\frac{H_l}{R} \right) \right] \right]} \right]$ Eqn. 4.14 BNL 1995

$fcon = \begin{pmatrix} 0.2 \\ 0.34 \\ 0.43 \end{pmatrix} Hz$ First three convective frequencies

$\rho_l := 1.71 \cdot 10^{-4} \cdot \frac{lbf \cdot sec^2}{in^4}$ waste density - specific gravity = 1.83

Determine Convective Pressures on the Tank Wall:

$$z := \begin{pmatrix} 24.5 \cdot in \\ 54.5 \cdot in \\ 90 \cdot in \\ 126.4 \cdot in \\ 160.25 \cdot in \\ 191.15 \cdot in \\ 222.05 \cdot in \\ 255.75 \cdot in \\ 291.75 \cdot in \\ 327.25 \cdot in \\ 362.25 \cdot in \\ 401.91 \cdot in \\ 438.26 \cdot in \end{pmatrix}$$

Vertical location of Euler element centroids at which pressures are reported.

$$\eta_l := \frac{z}{H_l}$$

Ratio of tank wall vertical location to waste height for waste element centroids.

$\eta_l =$

	0
0	0.054
1	0.121
2	0.199
3	0.28
4	0.355
5	0.423
6	0.491
7	0.566
8	0.645
9	0.724
10	0.801
11	0.889
12	0.97

Determine convective coefficients as a function of dimensionless height per BNL 1995 Eqn. 4.4

$$con_0(\eta_l) := \left[\frac{2}{(\lambda_0)^2 - 1} \cdot \frac{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$con_1(\eta_l) := \left[\frac{2}{(\lambda_1)^2 - 1} \cdot \frac{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$con_2(\eta_l) := \left[\frac{2}{(\lambda_2)^2 - 1} \cdot \frac{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$con_0(\eta_l) =$

	0
0	0.258
1	0.264
2	0.275
3	0.292
4	0.314
5	0.34
6	0.371
7	0.411
8	0.463
9	0.524
10	0.595
11	0.69
12	0.794

$con_1(\eta_l) =$

	0
0	$7.187 \cdot 10^{-4}$
1	$8.382 \cdot 10^{-4}$
2	$1.12 \cdot 10^{-3}$
3	$1.618 \cdot 10^{-3}$
4	$2.353 \cdot 10^{-3}$
5	$3.354 \cdot 10^{-3}$
6	$4.81 \cdot 10^{-3}$
7	$7.15 \cdot 10^{-3}$
8	0.011
9	0.017
10	0.025
11	0.04
12	0.062

$con_2(\eta_l) =$

	0
0	$1.167 \cdot 10^{-5}$
1	$1.666 \cdot 10^{-5}$
2	$2.995 \cdot 10^{-5}$
3	$5.831 \cdot 10^{-5}$
4	$1.102 \cdot 10^{-4}$
5	$1.977 \cdot 10^{-4}$
6	$3.55 \cdot 10^{-4}$
7	$6.727 \cdot 10^{-4}$
8	$1.332 \cdot 10^{-3}$
9	$2.611 \cdot 10^{-3}$
10	$5.072 \cdot 10^{-3}$
11	0.011
12	0.021

Impulsive pressure coefficient as a function of dimensionless wall height

$c_i(\eta_1) := 1 - con_0(\eta_1) - con_1(\eta_1) - con_2(\eta_1)$ Eqn. 4.7 BNL 1995

$c_i(\eta_1) =$

	0
0	0.741
1	0.736
2	0.724
3	0.706
4	0.683
5	0.657
6	0.624
7	0.581
8	0.525
9	0.457
10	0.375
11	0.259
12	0.123

Calculate maximum values of dynamic wall pressures from spectral acceleration of dome input TH.

Consider the first three convective mode spectral accelerations for the 0.5% damped spectrum

$SA_{c0} := 0.064 \cdot g$ $SA_{c0} = 24.73 \frac{in}{sec^2}$ Figure 2-24 of main report

$SA_{c1} := 0.108 \cdot g$ $SA_{c1} = 41.73 \frac{in}{sec^2}$

$SA_{c2} := 0.163 \cdot g$ $SA_{c2} = 62.98 \frac{in}{sec^2}$

Associate the impulsive mode with the ZPA, since the tank is rigid.

$PGA := 0.276 \cdot g$ $PGA = 106.65 \frac{in}{sec^2}$ ANSYS dome RS from Spectr - see also Figures 2-18 and 2-22 of main report.

$$p_{maxconv}(\eta_l,\theta) := \left[\sqrt{\left(con_0(\eta_l)\cdot SA_{c0}\right)^2 + \left(con_1(\eta_l)\cdot SA_{c1}\right)^2 + \left(con_2(\eta_l)\cdot SA_{c2}\right)^2}\right]\cdot\left(\rho_l\cdot R\cdot\cos(\theta\cdot deg)\right)$$

$$p_{maximpulsive}(\eta_l,\theta) := \left[\sqrt{\left[c_i(\eta_l)\cdot(PGA)\right]^2}\right]\cdot\left(\rho_l\cdot R\cdot\cos(\theta\cdot deg)\right)$$

$$p_{max}(\eta_l,\theta) := \left[\sqrt{\left[\left(c_i(\eta_l)\right)\cdot(PGA)\right]^2 + \left(con_0(\eta_l)\cdot SA_{c0}\right)^2 + \left(con_1(\eta_l)\cdot SA_{c1}\right)^2 + \left(con_2(\eta_l)\cdot SA_{c2}\right)^2}\right]\cdot\left(\rho_l\cdot R\cdot\cos(\theta\cdot deg)\right)$$

Eqn. 4.24 BNL 1995

$p_{maximpulsive}(\eta_l,0) =$ (units: $\frac{lbf}{in^2}$)

	0
0	6.08
1	6.037
2	5.943
3	5.794
4	5.607
5	5.389
6	5.122
7	4.768
8	4.306
9	3.748
10	3.075
11	2.122
12	1.009

Maximum impulsive dynamic pressures at theta = 0.

$p_{maxconv}(\eta_l,0) =$ (units: $\frac{lbf}{in^2}$)

	0
0	0.492
1	0.501
2	0.523
3	0.556
4	0.598
5	0.647
6	0.706
7	0.783
8	0.882
9	0.999
10	1.135
11	1.321
12	1.527

Maximum convective dynamic pressures at theta = 0.

$p_{max}(\eta_1, 0) =$

	0
0	6.1
1	6.058
2	5.966
3	5.821
4	5.638
5	5.428
6	5.171
7	4.832
8	4.395
9	3.879
10	3.278
11	2.5
12	1.83

$\frac{lbf}{in^2}$

Maximum total dynamic pressure at theta = 0.

$p_{max}(\eta_1, 45) =$

	0
0	4.313
1	4.284
2	4.218
3	4.116
4	3.987
5	3.838
6	3.656
7	3.417
8	3.108
9	2.743
10	2.318
11	1.768
12	1.294

$\frac{lbf}{in^2}$

Maximum total dynamic pressure at theta = 45 degrees.

$p_{max}(\eta_1, 90) =$

	0
0	0
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	0

$\frac{lbf}{in^2}$

Maximum total dynamic pressure at theta = 90 degrees.

Calculate Maximum Slosh Height:

$$\text{conmax} := \begin{pmatrix} 0.837 \\ 0.073 \\ 0.028 \end{pmatrix}$$ Maximum value of convective coefficients at η_l=1

$$h_{maxslosh} := R \cdot \sqrt{\left(\text{conmax}_0 \cdot \frac{SA_{c0}}{g}\right)^2 + \left(\text{conmax}_1 \cdot \frac{SA_{c1}}{g}\right)^2 + \left(\text{conmax}_2 \cdot \frac{SA_{c2}}{g}\right)^2}$$ Eqn. 4.60 BNL 1995

$$h_{maxslosh} = 24.45\,\text{in}$$ Maximum theoretical slosh height

Calculate Maximum Total Hydrodynamic Force:

The maximum hydrodynamic force induced on the tank wall is given by Eqn. 4.31 of BNL 1995 with the instantaneous accelerations replaced by the maximum spectral accelerations. First determine the effective impulsive and convective masses.

$$m_{lapprox} := \pi \cdot R^2 \cdot H_l \cdot \rho_l \qquad m_{lapprox} = 4.92 \times 10^4 \, \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}}$$ Total waste mass based on circular cylinder approximation.

$$m_l := 4.88 \cdot 10^4 \cdot \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}}$$ Actual waste mass reported by ANSYS model.

$$m_{c0} := \left[\frac{2}{\lambda_0 \cdot \left[\left(\lambda_0\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$ Eqn. 4.32 BNL 1995

$$m_{c0} = 2.1 \times 10^4 \, \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}}$$ First mode convective mass

$$m_{c1} := \left[\frac{2}{\lambda_1 \cdot \left[\left(\lambda_1\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$ Second mode convective mass

$m_{c1} = 664.71 \frac{lbf \cdot sec^2}{in}$

$m_{c2} := \left[\frac{2}{\lambda_2 \cdot \left[(\lambda_2)^2 - 1 \right] \cdot \left(\frac{H_l}{R} \right)} \right] \cdot \tanh\left[\lambda_2 \cdot \left(\frac{H_l}{R} \right) \right] \cdot m_l$ Third mode convective mass

$m_{c2} = 158.4 \frac{lbf \cdot sec^2}{in}$

$m_i := m_l - (m_{c0} + m_{c1} + m_{c2})$ Impulsive mass Eqn. 4.33 BNL 1995

$m_i = 2.7 \times 10^4 \frac{lbf \cdot sec^2}{in}$

$F_{max} := m_i \cdot PGA + m_{c0} \cdot SA_{c0} + m_{c1} \cdot SA_{c1} + m_{c2} \cdot SA_{c2}$ Eqn. 4.31 BNL 1995

$F_{max} = 3.43 \times 10^6 \, lbf$ Conservative estimate of maximum hydrodynamic force

The above expression is a conservative estimate because it assumes that the peak impulsive and convective forces occur simultaneously. A less conservative estimate can be made via a square-root-sum-of-the-squares (SRSS) combination.

$F_{srss} := \sqrt{(m_i \cdot PGA)^2 + (m_{c0} \cdot SA_{c0})^2 + (m_{c1} \cdot SA_{c1})^2 + (m_{c2} \cdot SA_{c2})^2}$ Eqn. 4.31 BNL 1995 - SRSS

$F_{srss} = 2.92 \times 10^6 \, lbf$ SRSS estimate of peak hydrodynamic force

$F_{conmax} := \sqrt{(m_{c0} \cdot SA_{c0})^2 + (m_{c1} \cdot SA_{c1})^2 + (m_{c2} \cdot SA_{c2})^2}$

$F_{conmax} = 5.21 \times 10^5 \, lbf$ Peak hydrodynamic force due to convective response - shows up in free oscillations.

Consider Vertical Excitation:

For a rigid tank, the period of the breathing mode is zero and the associated spectral acceleration is the vertical ZPA.

$ZPA_{vert} := 0.12 \cdot g$ ANSYS Haunch RS from Spectr

The maximum wall pressure as a function of the dimensionless vertical distance is given by

$p_{maxv}(\eta_l) := (0.8) \cdot \left(\cos\left(\frac{\pi}{2} \cdot \eta_l\right)\right) \cdot (\rho_l \cdot H_l \cdot ZPA_{vert})$ Eqn. 4.52 BNL 1995

$p_{maxv}(\eta_l) =$ (in $\frac{lbf}{in^2}$)

	0
0	2.857
1	2.816
2	2.728
3	2.595
4	2.434
5	2.257
6	2.055
7	1.807
8	1.515
9	1.204
10	0.88
11	0.497
12	0.137

The maximum base pressure and force are given by

$p_{maxbasevert} := \rho_l \cdot H_l \cdot ZPA_{vert}$ $p_{maxbasevert} = 3.58 \frac{lbf}{in^2}$ Eqn. 4.55 BNL 1995

$F_{maxbasevert} := m_l \cdot ZPA_{vert}$ $F_{maxbasevert} = 2.26 \times 10^6 \, lbf$ Eqn. 4.57 BNL 1995

Prepared by: F. G. Abatt
M&D Professional Services
10/11/05
Rev. 1

Theoretical Fluid Response
Calculations for Rigid Primary Tank
at 460 in. Waste Level
ANSYS Model Configuration

Checked by: B.G. Carpenter
M&D Professional Services
2/1/06

$H_l := 460.0 \cdot in$ Baseline waste level

$H_t := 460.0 \cdot in$ Height to primary tank tangent line

$\frac{H_l}{H_t} = 1$ Ratio of waste height to tank height

$g := 386.4 \cdot \frac{in}{sec^2}$

$R := 450 \cdot in$ Tank radius

$\frac{H_l}{R} = 1.02$ Ratio of waste height to tank radius

$i := 0..2$

$\lambda := \begin{pmatrix} 1.841 \\ 5.331 \\ 8.536 \end{pmatrix}$ Bessel function roots

$\theta := \begin{pmatrix} 0 \cdot deg \\ 45 \cdot deg \\ 90 \cdot deg \end{pmatrix}$ Circumferential location of waste elements for which pressures are reported

Convective Frequencies

$fcon_i := \frac{1}{2 \cdot \pi} \cdot \left[\sqrt{\lambda_i \left[\frac{g}{R} \cdot \tanh\left[\lambda_i \cdot \left(\frac{H_l}{R} \right) \right] \right]} \right]$ Eqn. 4.14 BNL 1995

$fcon = \begin{pmatrix} 0.2 \\ 0.34 \\ 0.43 \end{pmatrix} Hz$ First three convective frequencies

$\rho_l := 1.71 \cdot 10^{-4} \cdot \frac{lbf \cdot sec^2}{in^4}$ waste density - specific gravity = 1.83

Determine Convective Pressures on the Tank Wall:

$$z := \begin{pmatrix} 24.5\cdot in \\ 54.5\cdot in \\ 90.0\cdot in \\ 126.4\cdot in \\ 160.25\cdot in \\ 191.15\cdot in \\ 222.05\cdot in \\ 255.75\cdot in \\ 291.75\cdot in \\ 327.25\cdot in \\ 362.25\cdot in \\ 401.9\cdot in \\ 438.3\cdot in \\ 456.1\cdot in \end{pmatrix}$$

Vertical location of element centroids at which pressures are reported.

$$\eta_l := \frac{z}{H_l}$$

Ratio of tank wall vertical location to waste height for waste element centroids.

$\eta_l =$

	0
0	0.053
1	0.118
2	0.196
3	0.275
4	0.348
5	0.416
6	0.483
7	0.556
8	0.634
9	0.711
10	0.788
11	0.874
12	0.953
13	0.992

Determine convective coefficients as a function of dimensionless height per BNL 1995 Eqn. 4.4

$$con_0(\eta_l) := \left[\frac{2}{\left(\lambda_0\right)^2 - 1} \cdot \frac{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$con_1(\eta_l) := \left[\frac{2}{\left(\lambda_1\right)^2 - 1} \cdot \frac{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$con_2(\eta_l) := \left[\frac{2}{\left(\lambda_2\right)^2 - 1} \cdot \frac{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$con_0(\eta_l) =$

	0
0	0.25
1	0.255
2	0.266
3	0.283
4	0.305
5	0.329
6	0.359
7	0.398
8	0.449
9	0.508
10	0.577
11	0.669
12	0.769
13	0.824

$con_1(\eta_l) =$

	0
0	$6.537 \cdot 10^{-4}$
1	$7.624 \cdot 10^{-4}$
2	$1.019 \cdot 10^{-3}$
3	$1.472 \cdot 10^{-3}$
4	$2.14 \cdot 10^{-3}$
5	$3.051 \cdot 10^{-3}$
6	$4.375 \cdot 10^{-3}$
7	$6.503 \cdot 10^{-3}$
8	$9.948 \cdot 10^{-3}$
9	0.015
10	0.023
11	0.037
12	0.056
13	0.07

$con_2(\eta_l) =$

	0
0	$1.003 \cdot 10^{-5}$
1	$1.431 \cdot 10^{-5}$
2	$2.573 \cdot 10^{-5}$
3	$5.01 \cdot 10^{-5}$
4	$9.466 \cdot 10^{-5}$
5	$1.698 \cdot 10^{-4}$
6	$3.05 \cdot 10^{-4}$
7	$5.78 \cdot 10^{-4}$
8	$1.144 \cdot 10^{-3}$
9	$2.243 \cdot 10^{-3}$
10	$4.358 \cdot 10^{-3}$
11	$9.245 \cdot 10^{-3}$
12	0.018
13	0.026

Impulsive pressure coefficient as a function of dimensionless wall height

$c_i(\eta_1) := 1 - con_0(\eta_1) - con_1(\eta_1) - con_2(\eta_1)$ BNL 1995 Eqn. 4.7

$c_i(\eta_1) =$

	0
0	0.749
1	0.744
2	0.733
3	0.715
4	0.693
5	0.667
6	0.636
7	0.594
8	0.54
9	0.475
10	0.396
11	0.285
12	0.156
13	0.08

Calculate maximum values of dynamic wall pressures from spectral acceleration of dome input TH.

Consider the first three convective mode spectral accelerations for the 0.5% damped spectrum

$SA_{c0} := 0.064 \cdot g$ $SA_{c0} = 24.73 \frac{in}{sec^2}$ Figure 2-24 of main report

$SA_{c1} := 0.108 \cdot g$ $SA_{c1} = 41.73 \frac{in}{sec^2}$

$SA_{c2} := 0.163 \cdot g$ $SA_{c2} = 62.98 \frac{in}{sec^2}$

Associate the impulsive mode with the ZPA, since the tank is rigid.

$PGA := 0.276 \cdot g$ $PGA = 106.65 \frac{in}{sec^2}$ ANSYS dome RS from Spectr - see also Figures 2-18 and 2-22 of main report.

$$p_{maxconv}(\eta_1,\theta) := \left[\sqrt{\left(con_0(\eta_1)\cdot SA_{c0}\right)^2 + \left(con_1(\eta_1)\cdot SA_{c1}\right)^2 + \left(con_2(\eta_1)\cdot SA_{c2}\right)^2}\right]\cdot\left(\rho_l\cdot R\cdot\cos(\theta\cdot deg)\right)$$

$$p_{maximpulsive}(\eta_1,\theta) := \left[\sqrt{\left[c_i(\eta_1)\cdot(PGA)\right]^2}\right]\cdot\left(\rho_l\cdot R\cdot\cos(\theta\cdot deg)\right)$$

$$p_{max}(\eta_1,\theta) := \left[\sqrt{\left[\left(c_i(\eta_1)\right)\cdot(PGA)\right]^2 + \left(con_0(\eta_1)\cdot SA_{c0}\right)^2 + \left(con_1(\eta_1)\cdot SA_{c1}\right)^2 + \left(con_2(\eta_1)\cdot SA_{c2}\right)^2}\right]\cdot\left(\rho_l\cdot R\cdot\cos(\theta\cdot deg)\right)$$

Eqn. 4.24 BNL 1995

$p_{maximpulsive}(\eta_1, 0) =$ (units: $\frac{lbf}{in^2}$)

	0
0	6.146
1	6.104
2	6.013
3	5.869
4	5.688
5	5.477
6	5.22
7	4.878
8	4.432
9	3.895
10	3.25
11	2.339
12	1.279
13	0.657

Maximum impulsive dynamic pressures at theta = 0.

$p_{maxconv}(\eta_1, 0) =$ (units: $\frac{lbf}{in^2}$)

	0
0	0.477
1	0.486
2	0.507
3	0.539
4	0.58
5	0.627
6	0.684
7	0.759
8	0.855
9	0.968
10	1.1
11	1.279
12	1.478
13	1.59

Maximum convective dynamic pressures at theta = 0.

$p_{max}(\eta_1, 0) =$ (lbf/in²)

	0
0	6.164
1	6.123
2	6.034
3	5.894
4	5.717
5	5.513
6	5.264
7	4.937
8	4.514
9	4.014
10	3.431
11	2.666
12	1.954
13	1.72

$\frac{lbf}{in^2}$

Maximum total dynamic pressure at theta = 0.

$p_{max}(\eta_1, 45) =$

	0
0	4.359
1	4.33
2	4.267
3	4.168
4	4.043
5	3.898
6	3.722
7	3.491
8	3.192
9	2.838
10	2.426
11	1.885
12	1.382
13	1.216

$\frac{lbf}{in^2}$

Maximum total dynamic pressure at theta = 45 degrees.

$p_{max}(\eta_1, 90) =$

	0
0	0
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	0
13	0

$\frac{lbf}{in^2}$

Maximum total dynamic pressure at theta = 90 degrees.

Calculate Maximum Slosh Height:

$$\text{conmax} := \begin{pmatrix} 0.837 \\ 0.073 \\ 0.028 \end{pmatrix}$$

Maximum value of convective coefficients at η_l=1

$$h_{maxslosh} := R \cdot \sqrt{\left(\text{conmax}_0 \cdot \frac{SA_{c0}}{g}\right)^2 + \left(\text{conmax}_1 \cdot \frac{SA_{c1}}{g}\right)^2 + \left(\text{conmax}_2 \cdot \frac{SA_{c2}}{g}\right)^2}$$

Eqn. 4.60 BNL 1995

$$h_{maxslosh} = 24.45\,\text{in}$$

Maximum theoretical slosh height

Calculate Maximum Total Hydrodynamic Force:

The maximum hydrodynamic force induced on the tank wall is given by Eqn. 4.31 of BNL 1995 with the instantaneous accelerations replaced by the maximum spectral accelerations. First determine the effective impulsive and convective masses.

$$m_{lapprox} := \pi \cdot R^2 \cdot H_l \cdot \rho_l \qquad m_{lapprox} = 5 \times 10^4 \, \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}}$$

Total waste mass based on circular cylinder approximation.

$$m_l := 4.96 \cdot 10^4 \cdot \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}}$$

Actual waste mass reported by ANSYS model.

$$m_{c0} := \left[\frac{2}{\lambda_0 \cdot \left[\left(\lambda_0\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$

Eqn. 4.32 BNL 1995

$$m_{c0} = 2.11 \times 10^4 \, \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}}$$

First mode convective mass

$$m_{c1} := \left[\frac{2}{\lambda_1 \cdot \left[\left(\lambda_1\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$

Second mode convective mass

$m_{c1} = 663.87 \frac{lbf \cdot sec^2}{in}$

$m_{c2} := \left[\frac{2}{\lambda_2 \cdot \left[(\lambda_2)^2 - 1 \right] \cdot \left(\frac{H_l}{R} \right)} \right] \cdot \tanh\left[\lambda_2 \cdot \left(\frac{H_l}{R} \right) \right] \cdot m_l$ Third mode convective mass

$m_{c2} = 158.2 \frac{lbf \cdot sec^2}{in}$

$m_i := m_l - (m_{c0} + m_{c1} + m_{c2})$ Impulsive mass Eqn. 4.33 BNL 1995

$m_i = 2.77 \times 10^4 \frac{lbf \cdot sec^2}{in}$

$F_{max} := m_i \cdot PGA + m_{c0} \cdot SA_{c0} + m_{c1} \cdot SA_{c1} + m_{c2} \cdot SA_{c2}$ Eqn. 4.31 BNL 1995 - SRSS

$F_{max} = 3.51 \times 10^6 \, lbf$ Conservative estimate of maximum hydrodynamic force

The above expression is a conservative estimate because it assumes that the peak impulsive and convective forces occur simultaneously. A less conservative estimate can be made via a square-root-sum-of-the-squares (SRSS) combination.

$F_{srss} := \sqrt{(m_i \cdot PGA)^2 + (m_{c0} \cdot SA_{c0})^2 + (m_{c1} \cdot SA_{c1})^2 + (m_{c2} \cdot SA_{c2})^2}$

$F_{srss} = 3 \times 10^6 \, lbf$ SRSS estimate of peak hydrodynamic force

$F_{conmax} := \sqrt{(m_{c0} \cdot SA_{c0})^2 + (m_{c1} \cdot SA_{c1})^2 + (m_{c2} \cdot SA_{c2})^2}$

$F_{conmax} = 5.22 \times 10^5 \, lbf$ Peak hydrodynamic force due to convective response - shows up in free oscillations.

Consider Vertical Excitation:

For a rigid tank, the period of the breathing mode is zero and the associated spectral acceleration is the vertical ZPA.

$ZPA_{vert} := 0.12 \cdot g$ ANSYS Haunch RS from Spectr - see also Figure 2-19 of main report

The maximum wall pressure as a function of the dimensionless vertical distance is given by

$$p_{maxv}(\eta_l) := (0.8) \cdot \left(\cos\left(\frac{\pi}{2} \cdot \eta_l\right)\right) \cdot \left(\rho_l \cdot H_l \cdot ZPA_{vert}\right)$$ Eqn. 4.52 BNL 1995

$p_{maxv}(\eta_l) =$ (values in $\frac{lbf}{in^2}$)

	0
0	2.908
1	2.867
2	2.781
3	2.65
4	2.492
5	2.318
6	2.118
7	1.874
8	1.586
9	1.278
10	0.956
11	0.575
12	0.216
13	0.039

The maximum base pressure and force are given by

$p_{maxbasevert} := \rho_l \cdot H_l \cdot ZPA_{vert}$ $p_{maxbasevert} = 3.65 \frac{lbf}{in^2}$ Eqn. 4.55 BNL 1995

$F_{maxbasevert} := m_l \cdot ZPA_{vert}$ $F_{maxbasevert} = 2.3 \times 10^6 \, lbf$ Eqn. 4.57 BNL 1995

Reference:

BNL 1995, *Seismic Design and Evaluation Guidelines for the Department of Energy High-Level Waste Storage Tanks and Appurtenances*, BNL 52361, Rev. 10/95, Brookhaven National Laboratory, Upton, New York.

$H_l := 424 \cdot in$ Baseline waste level as modeled in ANSYS

$H_t := 460 \cdot in$ Height to primary tank tangent line

$\frac{H_l}{H_t} = 0.92$ Ratio of waste height to tank height

$g := 386.4 \cdot \frac{in}{sec^2}$

$R := 450 \cdot in$ Tank radius

$\frac{H_l}{R} = 0.94$ Ratio of waste height to tank radius

$i := 0..2$

$\lambda := \begin{pmatrix} 1.841 \\ 5.331 \\ 8.536 \end{pmatrix}$ Bessel function roots

$\theta := \begin{pmatrix} 0 \cdot deg \\ 45 \cdot deg \\ 90 \cdot deg \end{pmatrix}$ Circumferential location of waste elements for which pressures are reported

Convective Frequencies

$fcon_i := \frac{1}{2 \cdot \pi} \cdot \left[\sqrt{\left[\lambda_i \left[\frac{g}{R} \cdot \tanh\left[\lambda_i \cdot \left(\frac{H_l}{R}\right)\right]\right]\right]}\right]$ Eqn. 4.14 BNL 1995

$fcon = \begin{pmatrix} 0.19 \\ 0.34 \\ 0.43 \end{pmatrix} Hz$ First three convective frequencies

$\rho_l := 1.59 \cdot 10^{-4} \cdot \frac{lbf \cdot sec^2}{in^4}$ waste density - specific gravity = 1.7

Calculation of Impulsive Frequency:

$\rho_t := 7.35 \cdot 10^{-4} \cdot \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}^4}$ Steel density

$t_{tw} := 0.65 \cdot \text{in}$ Average thickness of AY over lower 2/3.

$E_t := 29 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2}$ Elastic modulus for steel

$C_{iref} := 0.102$ Table 4.4 of BNL 1995. Hinged top support condition - estimated for H_l/H_t=0.92

$C_i := C_{iref} \cdot \sqrt{127 \cdot \frac{\left(\frac{t_{tw}}{R}\right)}{\left(\frac{\rho_l}{\rho_t}\right)}}$ Eqn. 4.18 BNL 1995

$C_i = 0.09$ Impulsive coefficient for frequency calculation

$f_i := \frac{1}{2 \cdot \pi} \cdot \frac{C_i}{H_l} \cdot \sqrt{\frac{E_t}{\rho_t}}$ $f_i = 7\text{Hz}$ Eqn. 4.16 BNL 1995

Determine Convective Pressures on the Tank Wall:

$$z := \begin{pmatrix} 24.5 \cdot \text{in} \\ 54.5 \cdot \text{in} \\ 90.0 \cdot \text{in} \\ 126.4 \cdot \text{in} \\ 160.25 \cdot \text{in} \\ 191.15 \cdot \text{in} \\ 222.05 \cdot \text{in} \\ 255.75 \cdot \text{in} \\ 291.75 \cdot \text{in} \\ 327.25 \cdot \text{in} \\ 362.25 \cdot \text{in} \\ 401.9 \cdot \text{in} \end{pmatrix}$$

Vertical location of element centroids at which pressures are reported.

$\eta_l := \frac{z}{H_l}$

Ratio of tank wall vertical location to waste height for waste element centroids.

$\eta_l =$

	0
0	0.06
1	0.13
2	0.21
3	0.3
4	0.38
5	0.45
6	0.52
7	0.6
8	0.69
9	0.77
10	0.85
11	0.95

Determine convective coefficients as a function of dimensionless height per BNL 1995 Eqn. 4.4

$$con_0(\eta_l) := \left[\frac{2}{\left(\lambda_0\right)^2 - 1} \cdot \frac{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$con_1(\eta_l) := \left[\frac{2}{\left(\lambda_1\right)^2 - 1} \cdot \frac{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$con_2(\eta_l) := \left[\frac{2}{\left(\lambda_2\right)^2 - 1} \cdot \frac{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$con_0(\eta_1) =$

	0
0	0.29
1	0.29
2	0.31
3	0.33
4	0.35
5	0.38
6	0.41
7	0.46
8	0.52
9	0.58
10	0.66
11	0.77

$con_1(\eta_1) =$

	0
0	$1 \cdot 10^{-3}$
1	$1.17 \cdot 10^{-3}$
2	$1.56 \cdot 10^{-3}$
3	$2.25 \cdot 10^{-3}$
4	$3.28 \cdot 10^{-3}$
5	$4.67 \cdot 10^{-3}$
6	$6.7 \cdot 10^{-3}$
7	$9.96 \cdot 10^{-3}$
8	0.02
9	0.02
10	0.04
11	0.06

$con_2(\eta_1) =$

	0
0	$1.99 \cdot 10^{-5}$
1	$2.83 \cdot 10^{-5}$
2	$5.09 \cdot 10^{-5}$
3	$9.92 \cdot 10^{-5}$
4	$1.87 \cdot 10^{-4}$
5	$3.36 \cdot 10^{-4}$
6	$6.04 \cdot 10^{-4}$
7	$1.14 \cdot 10^{-3}$
8	$2.26 \cdot 10^{-3}$
9	$4.44 \cdot 10^{-3}$
10	$8.63 \cdot 10^{-3}$
11	0.02

Impulsive pressure coefficient as a function of dimensionless wall height

$c_i(\eta_1) := 1 - con_0(\eta_1) - con_1(\eta_1) - con_2(\eta_1)$ Eqn. 4.7 BNL 1995

$c_i(\eta_1) =$

	0
0	0.71
1	0.71
2	0.69
3	0.67
4	0.65
5	0.62
6	0.58
7	0.53
8	0.47
9	0.39
10	0.29
11	0.16

Calculate maximum values of dynamic wall pressures from spectral acceleration of dome input TH.

Consider the first three convective modes

$SA_{c0} := 0.062 \cdot g$ $\quad SA_{c0} = 23.96 \frac{in}{sec^2}$

$SA_{c1} := 0.108 \cdot g$ $\quad SA_{c1} = 41.73 \frac{in}{sec^2}$ 0.5% Dome RS from Spectr - see Figure 2-24 of main report

$SA_{c2} := 0.163 \cdot g$ $\quad SA_{c2} = 62.98 \frac{in}{sec^2}$

Determine the spectral acceleration for the impulsive mode.

$SA_i := 0.876 \cdot g$ $\quad SA_i = 338.49 \frac{in}{sec^2}$ 4% Dome RS from Spectr - see Figure 2-22 of main report.

$$p_{maxconv}(\eta_1, \theta) := \left[\sqrt{\left(con_0(\eta_1) \cdot SA_{c0}\right)^2 + \left(con_1(\eta_1) \cdot SA_{c1}\right)^2 + \left(con_2(\eta_1) \cdot SA_{c2}\right)^2}\right] \cdot \left(\rho_l \cdot R \cdot \cos(\theta \cdot deg)\right)$$

$$p_{maximpulsive}(\eta_1, \theta) := \left[\sqrt{\left[c_i(\eta_1) \cdot (SA_i)\right]^2}\right] \cdot \left(\rho_l \cdot R \cdot \cos(\theta \cdot deg)\right)$$

$$p_{max}(\eta_1, \theta) := \left[\sqrt{\left[\left(c_i(\eta_1)\right) \cdot (SA_i)\right]^2 + \left(con_0(\eta_1) \cdot SA_{c0}\right)^2 + \left(con_1(\eta_1) \cdot SA_{c1}\right)^2 + \left(con_2(\eta_1) \cdot SA_{c2}\right)^2}\right] \cdot \left(\rho_l \cdot R \cdot \cos(\theta \cdot deg)\right)$$

Previous equation is Eqn. 4.24 from BNL 1995

$p_{maximpulsive}(\eta_1, 0) =$ $\frac{lbf}{in^2}$

	0
0	17.22
1	17.08
2	16.77
3	16.27
4	15.65
5	14.93
6	14.04
7	12.85
8	11.3
9	9.41
10	7.1
11	3.78

Maximum impulsive dynamic pressures at theta = 0.

$p_{maxconv}(\eta_1, 0) =$ $\frac{lbf}{in^2}$

	0
0	0.49
1	0.5
2	0.52
3	0.56
4	0.6
5	0.65
6	0.71
7	0.79
8	0.89
9	1
10	1.14
11	1.33

Maximum convective dynamic pressures at theta = 0.

$p_{max}(\eta_1, 0) =$ $\frac{lbf}{in^2}$

	0
0	17.23
1	17.09
2	16.77
3	16.28
4	15.66
5	14.94
6	14.06
7	12.88
8	11.33
9	9.46
10	7.19
11	4.01

Maximum total dynamic pressure at theta = 0.

$p_{max}(\eta_1, 45) =$ (lbf/in²)

	0
0	12.18
1	12.08
2	11.86
3	11.51
4	11.07
5	10.56
6	9.94
7	9.11
8	8.01
9	6.69
10	5.08
11	2.84

$\frac{lbf}{in^2}$

Maximum total dynamic pressure at theta = 45 degrees.

$p_{max}(\eta_1, 90) =$

	0
0	0
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0

$\frac{lbf}{in^2}$

Maximum total dynamic pressure at theta = 90 degrees.

Calculate Maximum Slosh Height:

$$conmax := \begin{pmatrix} 0.837 \\ 0.073 \\ 0.028 \end{pmatrix}$$

Maximum value of convective coefficients at η_l=1

$$h_{maxslosh} := R \cdot \sqrt{\left(conmax_0 \cdot \frac{SA_{c0}}{g}\right)^2 + \left(conmax_1 \cdot \frac{SA_{c1}}{g}\right)^2 + \left(conmax_2 \cdot \frac{SA_{c2}}{g}\right)^2}$$

Eqn. 4.60 BNL 1995

$h_{maxslosh} = 23.71\, in$

Calculate Maximum Total Hydrodynamic Force:

The maximum hydrodynamic force induced on the tank wall is given by Eqn. 4.31 of BNL 1995 with the instantaneous accelerations replaced by the maximum spectral accelerations. First determine the effective impulsive and convective masses.

$m_{lapprox} := \pi \cdot R^2 \cdot H_l \cdot \rho_l \qquad m_{lapprox} = 4.29 \times 10^4 \frac{lbf \cdot sec^2}{in}$ Total waste mass base on circular cylinder approximation.

$m_l := 4.27 \times 10^4 \cdot \frac{lbf \cdot sec^2}{in}$ Actual waste mass reported by ANSYS model.

$$m_{c0} := \left[\frac{2}{\lambda_0 \cdot \left[\left(\lambda_0 \right)^2 - 1 \right] \cdot \left(\frac{H_l}{R} \right)} \right] \cdot \tanh\left[\lambda_0 \cdot \left(\frac{H_l}{R} \right) \right] \cdot m_l$$

First mode convective mass - Eqn. 4.32 BNL 1995

$$m_{c0} = 1.94 \times 10^4 \frac{lbf \cdot sec^2}{in}$$

$$m_{c1} := \left[\frac{2}{\lambda_1 \cdot \left[\left(\lambda_1 \right)^2 - 1 \right] \cdot \left(\frac{H_l}{R} \right)} \right] \cdot \tanh\left[\lambda_1 \cdot \left(\frac{H_l}{R} \right) \right] \cdot m_l$$

Second mode convective mass

$$m_{c1} = 620.01 \frac{lbf \cdot sec^2}{in}$$

$$m_{c2} := \left[\frac{2}{\lambda_2 \cdot \left[\left(\lambda_2 \right)^2 - 1 \right] \cdot \left(\frac{H_l}{R} \right)} \right] \cdot \tanh\left[\lambda_2 \cdot \left(\frac{H_l}{R} \right) \right] \cdot m_l$$

Third mode convective mass

$$m_{c2} = 147.76 \frac{lbf \cdot sec^2}{in}$$

$m_i := m_l - \left(m_{c0} + m_{c1} + m_{c2} \right)$ Impulsive mass - Eqn. 4.33 BNL 1995

$$m_i = 2.26 \times 10^4 \frac{lbf \cdot sec^2}{in}$$

$F_{max} := m_i \cdot SA_i + m_{c0} \cdot SA_{c0} + m_{c1} \cdot SA_{c1} + m_{c2} \cdot SA_{c2}$ Eqn. 4.31 BNL 1995

$F_{max} = 8.14 \times 10^6 \text{ lbf}$ Conservative estimate of maximum hydrodynamic force

The above expression is a conservative estimate because it assumes that the peak impulsive and convective forces occur simultaneously. A less conservative estimate can be made via a square-root-sum-of-the-squares (SRSS) combination.

$F_{srss} := \sqrt{(m_i \cdot SA_i)^2 + (m_{c0} \cdot SA_{c0})^2 + (m_{c1} \cdot SA_{c1})^2 + (m_{c2} \cdot SA_{c2})^2}$ Eqn. 4.31 BNL 1995 - SRSS

$F_{srss} = 7.65 \times 10^6 \text{ lbf}$ SRSS estimate of peak hydrodynamic force

$F_{con} := \sqrt{(m_{c0} \cdot SA_{c0})^2 + (m_{c1} \cdot SA_{c1})^2 + (m_{c2} \cdot SA_{c2})^2}$

$F_{con} = 4.65 \times 10^5 \text{ lbf}$ Peak hydrodynamic force due to convective effects only

Consider Vertical Excitation:

Calculate the axisymmetric breathing mode frequency for the tank

$C_{vref} := 0.088$ Table 4.17 BNL 1995

$C_v := C_{vref} \cdot \sqrt{127 \cdot \frac{\left(\frac{t_{tw}}{R}\right)}{\left(\frac{\rho_l}{\rho_t}\right)}}$ $C_v = 0.081$

$f_v := \frac{1}{2 \cdot \pi} \cdot \frac{C_v}{H_l} \cdot \sqrt{\frac{E_t}{\rho_t}}$ $f_v = 6.04 \text{Hz}$ Eqn. 4.53 BNL 1995

$s_{Av} := 0.53 \cdot g$ $s_{Av} = 204.79 \frac{\text{in}}{\text{sec}^2}$ Vert. Haunch 4 % RS from Spectr - see also Figure 2-22 of main report.

The maximum dynamic wall pressure as a function of the dimensionless vertical distance is given by

$p_{maxv}(\eta_l) := (0.8) \cdot \left(\cos\left(\frac{\pi}{2} \cdot \eta_l\right)\right) \cdot (\rho_l \cdot H_l \cdot s_{Av})$ Eqn. 4.52 BNL 1995

$p_{maxv}(\eta_l) =$

	0
0	11
1	10.82
2	10.44
3	9.86
4	9.16
5	8.39
6	7.51
7	6.45
8	5.2
9	3.87
10	2.5
11	0.9

$\frac{lbf}{in^2}$

$c_{oprimeouter} := 0.28$ $\quad c_{oprimecenter} := 0.54$ Estimated from Figure 4.7 BNL 1995

$c_{vprimeouter} := 0.72$ $\quad c_{vprimecenter} := 0.46$

$PGA_{vert} := 0.12 \cdot g$

The maximum base pressures at the outer and center elements are given by

$$p_{maxbasevertouter} := c_{oprimeouter} \cdot \rho_l \cdot H_l \cdot PGA_{vert} + c_{vprimeouter} \cdot (\rho_l \cdot H_l) \cdot S_{Av}$$ Eqn. 4.55 BNL 1995

$$p_{maxbasevertcenter} := c_{oprimecenter} \cdot \rho_l \cdot H_l \cdot PGA_{vert} + c_{vprimecenter} \cdot (\rho_l \cdot H_l) \cdot S_{Av}$$

$$p_{maxbasevertouter} = 10.82 \frac{lbf}{in^2}$$

$$p_{maxbasevertcenter} = 8.04 \frac{lbf}{in^2}$$

Determine the maximum vertical force on the base

$m_0 := 0.402 \cdot m_l$ Component of waste mass particpating in the motion of the tank base

$m_v := 0.598 \cdot m_l$ Component of waste mass particpating in the motion of the tank wall

BNL Table 4.17

$F_{maxbasevert} := \sqrt{\left(m_0 \cdot PGA_{vert}\right)^2 + \left(m_v \cdot S_{Av}\right)^2}$

Eqn. 4.57 BNL 1995 modified for maximum response per p. 4-34

$F_{maxbasevert} = 5.29 \times 10^6\ lbf$

$m_0 = 1.72 \times 10^4\ lbf \cdot \frac{sec^2}{in}$

$m_v = 2.55 \times 10^4\ lbf \cdot \frac{sec^2}{in}$

$H_l := 452 \cdot in$ Waste level as modeled in ANSYS

$H_t := 460 \cdot in$ Height to primary tank tangent line

$\frac{H_l}{H_t} = 0.98$ Ratio of waste height to tank height

$g := 386.4 \cdot \frac{in}{sec^2}$

$R := 450 \cdot in$ Tank radius

$\frac{H_l}{R} = 1$ Ratio of waste height to tank radius

$i := 0..2$

$\lambda := \begin{pmatrix} 1.841 \\ 5.331 \\ 8.536 \end{pmatrix}$ Bessel function roots

$\theta := \begin{pmatrix} 0 \cdot deg \\ 45 \cdot deg \\ 90 \cdot deg \end{pmatrix}$ Circumferential location of waste elements for which pressures are reported

Convective Frequencies

$fcon_i := \frac{1}{2 \cdot \pi} \cdot \left[\sqrt{\left[\lambda_i \left[\frac{g}{R} \cdot \tanh\left[\lambda_i \cdot \left(\frac{H_l}{R} \right) \right] \right] \right]} \right]$ Eqn. 4.14 BNL 1995

$fcon = \begin{pmatrix} 0.2 \\ 0.34 \\ 0.43 \end{pmatrix} Hz$ First three convective frequencies

$\rho_l := 1.71 \cdot 10^{-4} \cdot \frac{lbf \cdot sec^2}{in^4}$ waste density - specific gravity = 1.83

Calculation of Impulsive Frequency:

$\rho_t := 7.35 \cdot 10^{-4} \cdot \frac{lbf \cdot sec^2}{in^4}$ Steel density

$t_{tw} := 0.65 \cdot in$ Average thickness of AY over lower 2/3.

$E_t := 29 \cdot 10^6 \cdot \frac{lbf}{in^2}$ Elastic modulus for steel

$C_{iref} := 0.106$ Table 4.4 of BNL 1995. Hinged top support condition estimated for H_l/H_t=0.98

$C_i := C_{iref} \cdot \sqrt{127 \cdot \frac{\left(\frac{t_{tw}}{R}\right)}{\left(\frac{\rho_l}{\rho_t}\right)}}$ Eqn. 4.18 BNL 1995

$C_i = 0.09$ Impulsive coefficient for frequency calculation

$f_i := \frac{1}{2 \cdot \pi} \cdot \frac{C_i}{H_l} \cdot \sqrt{\frac{E_t}{\rho_t}}$ $f_i = 6.58\,Hz$ Eqn. 4.16 BNL 1995

Determine Convective Pressures on the Tank Wall:

$$z := \begin{pmatrix} 24.5 \cdot in \\ 54.5 \cdot in \\ 90.0 \cdot in \\ 126.4 \cdot in \\ 160.25 \cdot in \\ 191.15 \cdot in \\ 222.05 \cdot in \\ 255.75 \cdot in \\ 291.75 \cdot in \\ 327.25 \cdot in \\ 362.25 \cdot in \\ 401.9 \cdot in \\ 438.3 \cdot in \end{pmatrix}$$

Vertical location of element centroids at which pressures are reported.

$$\eta_l := \frac{z}{H_l}$$

Ratio of tank wall vertical location to waste height for waste element centroids.

$\eta_l =$

	0
0	0.05
1	0.12
2	0.2
3	0.28
4	0.35
5	0.42
6	0.49
7	0.57
8	0.65
9	0.72
10	0.8
11	0.89
12	0.97

Determine convective coefficients as a function of dimensionless height per BNL 1995 Eqn. 4.4

$$\mathrm{con}_0(\eta_l) := \left[\frac{2}{(\lambda_0)^2 - 1} \cdot \frac{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$\mathrm{con}_1(\eta_l) := \left[\frac{2}{(\lambda_1)^2 - 1} \cdot \frac{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$\mathrm{con}_2(\eta_l) := \left[\frac{2}{(\lambda_2)^2 - 1} \cdot \frac{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$con_0(\eta_1) =$

	0
0	0.26
1	0.26
2	0.27
3	0.29
4	0.31
5	0.34
6	0.37
7	0.41
8	0.46
9	0.52
10	0.6
11	0.69
12	0.79

$con_1(\eta_1) =$

	0
0	$7.19 \cdot 10^{-4}$
1	$8.38 \cdot 10^{-4}$
2	$1.12 \cdot 10^{-3}$
3	$1.62 \cdot 10^{-3}$
4	$2.35 \cdot 10^{-3}$
5	$3.35 \cdot 10^{-3}$
6	$4.81 \cdot 10^{-3}$
7	$7.15 \cdot 10^{-3}$
8	0.01
9	0.02
10	0.03
11	0.04
12	0.06

$con_2(\eta_1) =$

	0
0	$1.17 \cdot 10^{-5}$
1	$1.67 \cdot 10^{-5}$
2	$2.99 \cdot 10^{-5}$
3	$5.83 \cdot 10^{-5}$
4	$1.1 \cdot 10^{-4}$
5	$1.98 \cdot 10^{-4}$
6	$3.55 \cdot 10^{-4}$
7	$6.73 \cdot 10^{-4}$
8	$1.33 \cdot 10^{-3}$
9	$2.61 \cdot 10^{-3}$
10	$5.07 \cdot 10^{-3}$
11	0.01
12	0.02

Impulsive pressure coefficient as a function of dimensionless wall height

$c_i(\eta_1) := 1 - con_0(\eta_1) - con_1(\eta_1) - con_2(\eta_1)$ Eqn. 4.7 BNL 1995

$c_i(\eta_1) =$

	0
0	0.74
1	0.74
2	0.72
3	0.71
4	0.68
5	0.66
6	0.62
7	0.58
8	0.52
9	0.46
10	0.37
11	0.26
12	0.12

Calculate maximum values of dynamic wall pressures from spectral acceleration of dome input TH.

Consider the first three convective modes

$SA_{c0} := 0.064 \cdot g$ $\quad SA_{c0} = 24.73 \frac{in}{sec^2}$

$SA_{c1} := 0.108 \cdot g$ $\quad SA_{c1} = 41.73 \frac{in}{sec^2}$ 0.5% Dome RS from Spectr - see also Figure 2-24 of main report.

$SA_{c2} := 0.163 \cdot g$ $\quad SA_{c2} = 62.98 \frac{in}{sec^2}$

Determine the spectral acceleration for the impulsive mode.

$SA_i := 0.91 \cdot g$ $\quad SA_i = 351.62 \frac{in}{sec^2}$ 4% Dome RS from Spectr - see also Figure 2-22 of main report.

$$p_{maxconv}(\eta_1, \theta) := \left[\sqrt{\left(con_0(\eta_1) \cdot SA_{c0}\right)^2 + \left(con_1(\eta_1) \cdot SA_{c1}\right)^2 + \left(con_2(\eta_1) \cdot SA_{c2}\right)^2}\right] \cdot \left(\rho_l \cdot R \cdot \cos(\theta \cdot deg)\right)$$

$$p_{maximpulsive}(\eta_1, \theta) := \left[\sqrt{\left[c_i(\eta_1) \cdot (SA_i)\right]^2}\right] \cdot \left(\rho_l \cdot R \cdot \cos(\theta \cdot deg)\right)$$

$$p_{max}(\eta_1, \theta) := \left[\sqrt{\left[\left(c_i(\eta_1)\right) \cdot (SA_i)\right]^2 + \left(con_0(\eta_1) \cdot SA_{c0}\right)^2 + \left(con_1(\eta_1) \cdot SA_{c1}\right)^2 + \left(con_2(\eta_1) \cdot SA_{c2}\right)^2}\right] \cdot \left(\rho_l \cdot R \cdot \cos(\theta \cdot deg)\right)$$

Previous equation is Eqn. 4.24 BNL 1995

$p_{maximpulsive}(\eta_1, 0) =$ (units: $\frac{lbf}{in^2}$)

	0
0	20.05
1	19.9
2	19.59
3	19.11
4	18.49
5	17.77
6	16.89
7	15.72
8	14.2
9	12.36
10	10.14
11	7
12	3.32

Maximum impulsive dynamic pressures at theta = 0.

$p_{maxconv}(\eta_1, 0) =$ (units: $\frac{lbf}{in^2}$)

	0
0	0.49
1	0.5
2	0.52
3	0.56
4	0.6
5	0.65
6	0.71
7	0.78
8	0.88
9	1
10	1.14
11	1.32
12	1.53

Maximum convective dynamic pressures at theta = 0.

$p_{max}(\eta_1, 0) =$ (units: $\frac{lbf}{in^2}$)

	0
0	20.05
1	19.91
2	19.6
3	19.11
4	18.5
5	17.78
6	16.9
7	15.74
8	14.22
9	12.4
10	10.2
11	7.12
12	3.66

Maximum total dynamic pressure at theta = 0.

$p_{max}(\eta_l, 45) =$ (lbf/in²)

	0
0	14.18
1	14.08
2	13.86
3	13.52
4	13.08
5	12.57
6	11.95
7	11.13
8	10.06
9	8.77
10	7.21
11	5.04
12	2.59

$\frac{lbf}{in^2}$

Maximum total dynamic pressure at theta = 45 degrees.

$p_{max}(\eta_l, 90) =$

	0
0	0
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	0

$\frac{lbf}{in^2}$

Maximum total dynamic pressure at theta = 90 degrees.

<u>Calculate Maximum Slosh Height:</u>

$$conmax := \begin{pmatrix} 0.837 \\ 0.073 \\ 0.028 \end{pmatrix}$$

Maximum value of convective coefficients at η_l=1

$$h_{maxslosh} := R \cdot \sqrt{\left(conmax_0 \cdot \frac{SA_{c0}}{g}\right)^2 + \left(conmax_1 \cdot \frac{SA_{c1}}{g}\right)^2 + \left(conmax_2 \cdot \frac{SA_{c2}}{g}\right)^2}$$

Eqn. 4.60 BNL 1995

$$h_{maxslosh} = 24.45 in$$

Calculate Maximum Total Hydrodynamic Force:

The maximum hydrodynamic force induced on the tank wall is given by Eqn. 4.31 of BNL 1995 with the instantaneous accelerations replaced by the maximum spectral accelerations. First determine the effective impulsive and convective masses.

$m_{lapprox} := \pi \cdot R^2 \cdot H_l \cdot \rho_l \qquad m_{lapprox} = 4.92 \times 10^4 \, \frac{lbf \cdot sec^2}{in}$ Total waste mass base on circular cylinder approximation.

$m_l := 4.88 \times 10^4 \cdot \frac{lbf \cdot sec^2}{in}$ Actual waste mass reported by ANSYS model.

$$m_{c0} := \left[\frac{2}{\lambda_0 \cdot \left[\left(\lambda_0\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$

First mode convective mass - Eqn. 4.32 BNL 1995

$m_{c0} = 2.1 \times 10^4 \, \frac{lbf \cdot sec^2}{in}$

$$m_{c1} := \left[\frac{2}{\lambda_1 \cdot \left[\left(\lambda_1\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$

Second mode convective mass

$m_{c1} = 664.71 \, \frac{lbf \cdot sec^2}{in}$

$$m_{c2} := \left[\frac{2}{\lambda_2 \cdot \left[\left(\lambda_2\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$

Third mode convective mass

$m_{c2} = 158.4 \, \frac{lbf \cdot sec^2}{in}$

$m_i := m_l - \left(m_{c0} + m_{c1} + m_{c2}\right)$ Impulsive mass - Eqn. 4.33 BNL 1995

$m_i = 2.7 \times 10^4 \, \frac{lbf \cdot sec^2}{in}$

$F_{max} := m_i \cdot SA_i + m_{c0} \cdot SA_{c0} + m_{c1} \cdot SA_{c1} + m_{c2} \cdot SA_{c2}$ Eqn. 4.31 BNL 1995

$F_{max} = 1 \times 10^7 \, lbf$ Conservative estimate of maximum hydrodynamic force

The above expression is a conservative estimate because it assumes that the peak impulsive and convective forces occur simultaneously. A less conservative estimate can be made via a square-root-sum-of-the-squares (SRSS) combination.

$F_{srss} := \sqrt{(m_i \cdot SA_i)^2 + (m_{c0} \cdot SA_{c0})^2 + (m_{c1} \cdot SA_{c1})^2 + (m_{c2} \cdot SA_{c2})^2}$ Eqn. 4.31 BNL 1995 - SRSS

$F_{srss} = 9.49 \times 10^6 \, lbf$ SRSS estimate of peak hydrodynamic force

$F_{con} := \sqrt{(m_{c0} \cdot SA_{c0})^2 + (m_{c1} \cdot SA_{c1})^2 + (m_{c2} \cdot SA_{c2})^2}$

$F_{con} = 5.21 \times 10^5 \, lbf$ Peak hydrodynamic force due to convective effects only

<u>Consider Vertical Excitation:</u>

Calculate the axisymmetric breathing mode frequency for the tank

$C_{vref} := 0.089$ Table 4.17 BNL 1995

$C_v := C_{vref} \cdot \sqrt{127 \cdot \frac{\left(\frac{t_{tw}}{R}\right)}{\left(\frac{\rho_l}{\rho_t}\right)}}$ $C_v = 0.079$

$f_v := \frac{1}{2 \cdot \pi} \cdot \frac{C_v}{H_l} \cdot \sqrt{\frac{E_t}{\rho_t}}$ $f_v = 5.53 \, Hz$ Eqn. 4.53 BNL 1995

$S_{Av} := 0.40 \cdot g$ $S_{Av} = 154.56 \frac{in}{sec^2}$ Vert. Haunch 4 % RS from Spectr - see also Figure 2-22 of main report.

The maximum dynamic wall pressure as a function of the dimensionless vertical distance is given by

$p_{maxv}(\eta_l) := (0.8) \cdot \left(\cos\left(\frac{\pi}{2} \cdot \eta_l\right)\right) \cdot (\rho_l \cdot H_l \cdot S_{Av})$ Eqn. 4.52 BNL 1995

$p_{maxv}(\eta_l) =$ (lbf/in²)

	0
0	9.52
1	9.39
2	9.09
3	8.65
4	8.11
5	7.52
6	6.85
7	6.02
8	5.05
9	4.01
10	2.93
11	1.66
12	0.45

$c_{oprimeouter} := 0.28$ $c_{oprimecenter} := 0.54$ Estimated from Figure 4.7 BNL 1995

$c_{vprimeouter} := 0.72$ $c_{vprimecenter} := 0.46$

$PGA_{vert} := 0.12 \cdot g$ Figure 2-19 of main report

The maximum base pressures at the outer and center elements are given by

$$p_{maxbasevertouter} := c_{oprimeouter} \cdot \rho_l \cdot H_l \cdot PGA_{vert} + c_{vprimeouter} \cdot (\rho_l \cdot H_l) \cdot S_{Av}$$ Eqn. 4.55 BNL 1995

$$p_{maxbasevertcenter} := c_{oprimecenter} \cdot \rho_l \cdot H_l \cdot PGA_{vert} + c_{vprimecenter} \cdot (\rho_l \cdot H_l) \cdot S_{Av}$$

$$p_{maxbasevertouter} = 9.6 \frac{lbf}{in^2}$$

$$p_{maxbasevertcenter} = 7.43 \frac{lbf}{in^2}$$

Determine the maximum vertical force on the base

$m_0 := 0.388 \cdot m_l$ Component of waste mass particpating in the motion of the tank base

$m_v := 0.612 \cdot m_l$ Component of waste mass particpating in the motion of the tank wall

Table 4.17 BNL 1995

$F_{maxbasevert} := \sqrt{\left(m_0 \cdot PGA_{vert}\right)^2 + \left(m_v \cdot S_{Av}\right)^2}$

Eqn. 4.57 BNL 1995 modified for maximum response per p. 4-34.

$F_{maxbasevert} = 4.7 \times 10^6\ lbf$

$m_0 = 1.89 \times 10^4\ lbf \cdot \frac{sec^2}{in}$

$m_v = 2.99 \times 10^4\ lbf \cdot \frac{sec^2}{in}$

Reference:

BNL 1995, *Seismic Design and Evaluation Guidelines for the Department of Energy High-Level Waste Storage Tanks and Appurtenances*, BNL 52361, Rev. 10/95, Brookhaven National Laboratory, Upton, New York.

Prepared by: F. G. Abatt
M&D Professional Services
10/07/05
Rev. 2

Theoretical Fluid Response for Simplified AY Flexible Wall Tank at 460 in. Waste Level - ANSYS Model Configuration

Checked by: B.G. Carpenter
M&D Professional Services
2/1/06

$H_l := 460 \cdot in$ Waste level as modeled in ANSYS

$H_t := 460 \cdot in$ Height to primary tank tangent line

$\frac{H_l}{H_t} = 1$ Ratio of waste height to tank height

$g := 386.4 \cdot \frac{in}{sec^2}$

$R := 450 \cdot in$ Tank radius

$\frac{H_l}{R} = 1.02$ Ratio of waste height to tank radius

$i := 0..2$

$\lambda := \begin{pmatrix} 1.841 \\ 5.331 \\ 8.536 \end{pmatrix}$ Bessel function roots

$\theta := \begin{pmatrix} 0 \cdot deg \\ 45 \cdot deg \\ 90 \cdot deg \end{pmatrix}$ Circumferential location of waste elements for which pressures are reported

Convective Frequencies

$fcon_i := \frac{1}{2 \cdot \pi} \cdot \left[\sqrt{\left[\lambda_i \left[\frac{g}{R} \cdot \tanh \left[\lambda_i \cdot \left(\frac{H_l}{R} \right) \right] \right] \right]} \right]$ Eqn. 4.14 BNL 1995

$fcon = \begin{pmatrix} 0.2 \\ 0.34 \\ 0.43 \end{pmatrix} Hz$ First three convective frequencies

$\rho_l := 1.71 \cdot 10^{-4} \cdot \frac{lbf \cdot sec^2}{in^4}$ waste density - specific gravity = 1.83

Calculation of Impulsive Frequency:

$\rho_t := 7.35 \cdot 10^{-4} \cdot \frac{lbf \cdot sec^2}{in^4}$ Steel density

$t_{tw} := 0.65 \cdot in$ Average thickness of AY over lower 2/3.

$E_t := 29 \cdot 10^6 \cdot \frac{lbf}{in^2}$ Elastic modulus for steel

$C_{iref} := 0.1062$ Table 4.4 of BNL 1995. Hinged top support condition estimated for H_l/H_t=0.98

$$C_i := C_{iref} \cdot \sqrt{127 \cdot \frac{\left(\frac{t_{tw}}{R}\right)}{\left(\frac{\rho_l}{\rho_t}\right)}}$$ Eqn. 4.18 BNL 1995

$C_i = 0.09$ Impulsive coefficient for frequency calculation

$$f_i := \frac{1}{2 \cdot \pi} \cdot \frac{C_i}{H_l} \cdot \sqrt{\frac{E_t}{\rho_t}}$$ $f_i = 6.48 Hz$ Eqn. 4.16 BNL 1995

Determine Convective Pressures on the Tank Wall:

$$z := \begin{pmatrix} 24.5 \cdot in \\ 54.5 \cdot in \\ 90.0 \cdot in \\ 126.4 \cdot in \\ 160.25 \cdot in \\ 191.15 \cdot in \\ 222.05 \cdot in \\ 255.75 \cdot in \\ 291.75 \cdot in \\ 327.25 \cdot in \\ 362.25 \cdot in \\ 401.9 \cdot in \\ 438.3 \cdot in \\ 456.1 \cdot in \end{pmatrix}$$

Vertical location of element centroids at which pressures are reported.

$\eta_l := \frac{z}{H_l}$

Ratio of tank wall vertical location to waste height for waste element centroids.

$\eta_l =$

	0
0	0.05
1	0.12
2	0.2
3	0.27
4	0.35
5	0.42
6	0.48
7	0.56
8	0.63
9	0.71
10	0.79
11	0.87
12	0.95
13	0.99

Determine convective coefficients as a function of dimensionless height per BNL 1995 Eqn. 4.4

$$con_0(\eta_l) := \left[\frac{2}{(\lambda_0)^2 - 1} \cdot \frac{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$con_1(\eta_l) := \left[\frac{2}{(\lambda_1)^2 - 1} \cdot \frac{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$$con_2(\eta_l) := \left[\frac{2}{(\lambda_2)^2 - 1} \cdot \frac{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right) \cdot \eta_l\right]}{\cosh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right)\right]}\right]$$

$con_0(\eta_1) =$

	0
0	0.25
1	0.26
2	0.27
3	0.28
4	0.3
5	0.33
6	0.36
7	0.4
8	0.45
9	0.51
10	0.58
11	0.67
12	0.77
13	0.82

$con_1(\eta_1) =$

	0
0	$6.54 \cdot 10^{-4}$
1	$7.62 \cdot 10^{-4}$
2	$1.02 \cdot 10^{-3}$
3	$1.47 \cdot 10^{-3}$
4	$2.14 \cdot 10^{-3}$
5	$3.05 \cdot 10^{-3}$
6	$4.37 \cdot 10^{-3}$
7	$6.5 \cdot 10^{-3}$
8	$9.95 \cdot 10^{-3}$
9	0.02
10	0.02
11	0.04
12	0.06
13	0.07

$con_2(\eta_1) =$

	0
0	$1 \cdot 10^{-5}$
1	$1.43 \cdot 10^{-5}$
2	$2.57 \cdot 10^{-5}$
3	$5.01 \cdot 10^{-5}$
4	$9.47 \cdot 10^{-5}$
5	$1.7 \cdot 10^{-4}$
6	$3.05 \cdot 10^{-4}$
7	$5.78 \cdot 10^{-4}$
8	$1.14 \cdot 10^{-3}$
9	$2.24 \cdot 10^{-3}$
10	$4.36 \cdot 10^{-3}$
11	$9.24 \cdot 10^{-3}$
12	0.02
13	0.03

Impulsive pressure coefficient as a function of dimensionless wall height

$c_i(\eta_1) := 1 - con_0(\eta_1) - con_1(\eta_1) - con_2(\eta_1)$ Eqn. 4.7 BNL 1995

$c_i(\eta_1) =$

	0
0	0.75
1	0.74
2	0.73
3	0.72
4	0.69
5	0.67
6	0.64
7	0.59
8	0.54
9	0.47
10	0.4
11	0.29
12	0.16
13	0.08

Calculate maximum values of dynamic wall pressures from spectral acceleration of dome input TH.

Consider the first three convective modes

$SA_{c0} := 0.064 \cdot g$ $\quad SA_{c0} = 24.73 \frac{in}{sec^2}$

$SA_{c1} := 0.108 \cdot g$ $\quad SA_{c1} = 41.73 \frac{in}{sec^2}$

0.5% Dome RS from Spectr - see Figure 2-24 of main report.

$SA_{c2} := 0.163 \cdot g$ $\quad SA_{c2} = 62.98 \frac{in}{sec^2}$

Determine the spectral acceleration for the impulsive mode.

$SA_i := 0.98 \cdot g$ $\quad SA_i = 378.67 \frac{in}{sec^2}$

4% Dome RS from Spectr - see also Figure 2-19 of main report.

$$p_{maxconv}(\eta_1,\theta) := \left[\sqrt{\left(con_0(\eta_1)\cdot SA_{c0}\right)^2 + \left(con_1(\eta_1)\cdot SA_{c1}\right)^2 + \left(con_2(\eta_1)\cdot SA_{c2}\right)^2}\right]\cdot\left(\rho_l \cdot R \cdot \cos(\theta \cdot deg)\right)$$

$$p_{maximpulsive}(\eta_1,\theta) := \left[\sqrt{\left[c_i(\eta_1)\cdot(SA_i)\right]^2}\right]\cdot\left(\rho_l \cdot R \cdot \cos(\theta \cdot deg)\right)$$

$$p_{max}(\eta_1,\theta) := \left[\sqrt{\left[\left(c_i(\eta_1)\right)\cdot(SA_i)\right]^2 + \left(con_0(\eta_1)\cdot SA_{c0}\right)^2 + \left(con_1(\eta_1)\cdot SA_{c1}\right)^2 + \left(con_2(\eta_1)\cdot SA_{c2}\right)^2}\right]\cdot\left(\rho_l \cdot R \cdot \cos(\theta \cdot deg)\right)$$

Previous equation is Eqn. 4.24 BNL 1995

$p_{maximpulsive}(\eta_1, 0) =$

	0
0	21.82
1	21.67
2	21.35
3	20.84
4	20.2
5	19.45
6	18.53
7	17.32
8	15.74
9	13.83
10	11.54
11	8.3
12	4.54
13	2.33

$\frac{lbf}{in^2}$

Maximum impulsive dynamic pressures at theta = 0.

$p_{maxconv}(\eta_1, 0) =$

	0
0	0.48
1	0.49
2	0.51
3	0.54
4	0.58
5	0.63
6	0.68
7	0.76
8	0.85
9	0.97
10	1.1
11	1.28
12	1.48
13	1.59

$\frac{lbf}{in^2}$

Maximum convective dynamic pressures at theta = 0.

$p_{max}(\eta_1, 0) =$

	0
0	21.83
1	21.68
2	21.36
3	20.85
4	20.2
5	19.46
6	18.55
7	17.34
8	15.76
9	13.87
10	11.59
11	8.4
12	4.77
13	2.82

$\frac{lbf}{in^2}$

Maximum total dynamic pressure at theta = 0.

$p_{max}(\eta_l, 45) =$ (in $\frac{lbf}{in^2}$)

	0
0	15.43
1	15.33
2	15.1
3	14.74
4	14.29
5	13.76
6	13.11
7	12.26
8	11.15
9	9.8
10	8.2
11	5.94
12	3.38
13	2

Maximum total dynamic pressure at theta = 45 degrees.

$p_{max}(\eta_l, 90) =$ (in $\frac{lbf}{in^2}$)

	0
0	0
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	0
13	0

Maximum total dynamic pressure at theta = 90 degrees.

Calculate Maximum Slosh Height:

$$conmax := \begin{pmatrix} 0.837 \\ 0.073 \\ 0.028 \end{pmatrix}$$

Maximum value of convective coefficients at η_l=1

$$h_{maxslosh} := R \cdot \sqrt{\left(conmax_0 \cdot \frac{SA_{c0}}{g}\right)^2 + \left(conmax_1 \cdot \frac{SA_{c1}}{g}\right)^2 + \left(conmax_2 \cdot \frac{SA_{c2}}{g}\right)^2}$$

Eqn. 4.60 BNL 1995

$h_{maxslosh} = 24.45 in$

Calculate Maximum Total Hydrodynamic Force:

The maximum hydrodynamic force induced on the tank wall is given by Eqn. 4.31 of BNL 1995 with the instantaneous accelerations replaced by the maximum spectral accelerations. First determine the effective impulsive and convective masses.

$m_{lapprox} := \pi \cdot R^2 \cdot H_l \cdot \rho_l \qquad m_{lapprox} = 5 \times 10^4 \frac{lbf \cdot sec^2}{in}$

Total waste mass base on circular cylinder approximation.

$m_l := 4.96 \times 10^4 \cdot \frac{lbf \cdot sec^2}{in}$

Actual waste mass reported by ANSYS model.

$$m_{c0} := \left[\frac{2}{\lambda_0 \cdot \left[\left(\lambda_0\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_0 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$

First mode convective mass - Eqn. 4.32 BNL 1995

$m_{c0} = 2.11 \times 10^4 \frac{lbf \cdot sec^2}{in}$

$$m_{c1} := \left[\frac{2}{\lambda_1 \cdot \left[\left(\lambda_1\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_1 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$

Second mode convective mass

$m_{c1} = 663.87 \frac{lbf \cdot sec^2}{in}$

$$m_{c2} := \left[\frac{2}{\lambda_2 \cdot \left[\left(\lambda_2\right)^2 - 1\right] \cdot \left(\frac{H_l}{R}\right)}\right] \cdot \tanh\left[\lambda_2 \cdot \left(\frac{H_l}{R}\right)\right] \cdot m_l$$

Third mode convective mass

$m_{c2} = 158.2 \frac{lbf \cdot sec^2}{in}$

$m_i := m_l - \left(m_{c0} + m_{c1} + m_{c2}\right)$

Impulsive mass - Eqn. 4.33 BNL 1995

$m_i = 2.77 \times 10^4 \frac{lbf \cdot sec^2}{in}$

$F_{max} := m_i \cdot SA_i + m_{c0} \cdot SA_{c0} + m_{c1} \cdot SA_{c1} + m_{c2} \cdot SA_{c2}$ Eqn. 4.31 BNL 1995

$F_{max} = 1.11 \times 10^7\ \text{lbf}$ Conservative estimate of maximum hydrodynamic force

The above expression is a conservative estimate because it assumes that the peak impulsive and convective forces occur simultaneously. A less conservative estimate can be made via a square-root-sum-of-the-squares (SRSS) combination.

$F_{srss} := \sqrt{(m_i \cdot SA_i)^2 + (m_{c0} \cdot SA_{c0})^2 + (m_{c1} \cdot SA_{c1})^2 + (m_{c2} \cdot SA_{c2})^2}$ Eqn. 4.31 BNL 1995 - SRSS

$F_{srss} = 1.05 \times 10^7\ \text{lbf}$ SRSS estimate of peak hydrodynamic force

$F_{con} := \sqrt{(m_{c0} \cdot SA_{c0})^2 + (m_{c1} \cdot SA_{c1})^2 + (m_{c2} \cdot SA_{c2})^2}$

$F_{con} = 5.22 \times 10^5\ \text{lbf}$ Peak hydrodynamic force due to convective effects only

Consider Vertical Excitation:

Calculate the axisymmetric breathing mode frequency for the tank

$C_{vref} := 0.089$ Table 4.17 BNL 1995

$C_v := C_{vref} \cdot \sqrt{127 \cdot \frac{\left(\frac{t_{tw}}{R}\right)}{\left(\frac{\rho_l}{\rho_t}\right)}}$ $C_v = 0.079$ Eqn. 4.16 BNL 1995

$f_v := \frac{1}{2 \cdot \pi} \cdot \frac{C_v}{H_l} \cdot \sqrt{\frac{E_t}{\rho_t}}$ $f_v = 5.43\,\text{Hz}$ Eqn. 4.53 BNL 1995

$S_{Av} := 0.38 \cdot g$ $S_{Av} = 146.83 \frac{\text{in}}{\text{sec}^2}$ Vert. Haunch 4 % RS from Spectr - see also Figure 2-22 of main report.

The maximum dynamic wall pressure as a function of the dimensionless vertical distance is given by

$p_{maxv}(\eta_l) := (0.8) \cdot \left(\cos\left(\frac{\pi}{2} \cdot \eta_l\right)\right) \cdot (\rho_l \cdot H_l \cdot S_{Av})$ Eqn. 4.52 BNL 1995

$p_{maxv}(\eta_l) =$ (in $\frac{lbf}{in^2}$)

	0
0	9.21
1	9.08
2	8.81
3	8.39
4	7.89
5	7.34
6	6.71
7	5.93
8	5.02
9	4.05
10	3.03
11	1.82
12	0.68
13	0.12

$c_{oprimeouter} := 0.28$ $\quad c_{oprimecenter} := 0.54$ Estimated from Figure 4.7 BNL 1995

$c_{vprimeouter} := 0.72$ $\quad c_{vprimecenter} := 0.46$

$PGA_{vert} := 0.12 \cdot g$ Figure 2-19 of main report

The maximum base pressures at the outer and center elements are given by

$$p_{maxbasevertouter} := c_{oprimeouter} \cdot \rho_l \cdot H_l \cdot PGA_{vert} + c_{vprimeouter} \cdot (\rho_l \cdot H_l) \cdot S_{Av}$$ Eqn. 4.55 BNL 1995

$$p_{maxbasevertcenter} := c_{oprimecenter} \cdot \rho_l \cdot H_l \cdot PGA_{vert} + c_{vprimecenter} \cdot (\rho_l \cdot H_l) \cdot S_{Av}$$

$$p_{maxbasevertouter} = 9.34 \frac{lbf}{in^2}$$

$$p_{maxbasevertcenter} = 7.28 \frac{lbf}{in^2}$$

Determine the maximum vertical force on the base

$m_0 := 0.388 \cdot m_l$ Component of waste mass particpating in the motion of the tank base

$m_v := 0.612 \cdot m_l$ Component of waste mass particpating in the motion of the tank wall

BNL Table 4.17

$$F_{maxbasevert} := \sqrt{(m_0 \cdot PGA_{vert})^2 + (m_v \cdot S_{Av})^2}$$

Eqn. 4.57 BNL 1995 modified for maximum response per p. 4-34.

$$F_{maxbasevert} = 4.55 \times 10^6 \, lbf$$

$$m_0 = 1.92 \times 10^4 \, lbf \cdot \frac{sec^2}{in}$$

$$m_v = 3.04 \times 10^4 \, lbf \cdot \frac{sec^2}{in}$$

Reference:

BNL 1995, *Seismic Design and Evaluation Guidelines for the Department of Energy High-Level Waste Storage Tanks and Appurtenances*, BNL 52361, Rev. 10/95, Brookhaven National Laboratory, Upton, New York.

Appendix C

ANSYS Input File Listing

Tank-Coordinates-AP.txt

```
/COM - Definition of KeyPoints for Primary tank

ct_kps-34      ! Total number of Concrete tank
Coordinate pairs
pt_kps-36      ! Total number of Primary Tank
Coordinate pairs
bm_kp-22       ! Coordinate pair at bottom on
concrete tank wall
tw-9           ! Rings in commmon for insulating
concrete
arcsize-9      ! Control for meshing, section
angle
Midsize-5      ! Control for meshing, center
areas
z_off-56.56    ! Vertical offset for tank
(bottom of primary tank is Z-0 for coordinates)
C_Floor--4


*dim,ctx,,ct_kps       ! Concrete Tank Keypoint
X Coordinates
*dim,ctz,,ct_kps       ! Concrete Tank Keypoint
Z Coordinates
*dim,ptx,,pt_kps       ! Primary Tank Keypoint X
Coordinates
*dim,ptz,,pt_kps       ! Primary Tank Keypoint Z
Coordinates

/COM - Define Horizontal Keypoint Locations
ctx(1)-0
ctx(2)-45/12
ctx(3)-90.4/12
ctx(4)-120.72/12
ctx(5)-152.9/12
ctx(6)-211.4/12
ctx(7)-239.1/12
ctx(8)-306.63/12
ctx(9)-335.6/12
ctx(10)-393.7/12
ctx(11)-428.7/12
ctx(12)-469.9/12
ctx(13)-486.9/12
ctx(14)-489/12
ctx(15)-489/12
ctx(16)-489/12
ctx(17)-489/12
ctx(18)-489/12
ctx(19)-489/12
ctx(20)-489/12
ctx(21)-489/12
ctx(22)-489/12
ctx(23)-531/12
ctx(24)-489/12
ctx(25)-438/12
ctx(26)-410/12
ctx(27)-358/12
ctx(28)-277.7/12
ctx(29)-218.5/12
ctx(30)-180/12
ctx(31)-129.9/12
ctx(32)-95.7/12
ctx(33)-36/12
ctx(34)-0

/COM - Define Vertical Keypoint Locations
ctz(1)-568.8/12-z_off
ctz(2)-568/12-z_off
ctz(3)-565.8/12-z_off
ctz(4)-563.21/12-z_off
ctz(5)-559.7/12-z_off
ctz(6)-550.7/12-z_off
ctz(7)-545.2/12-z_off
ctz(8)-527.68/12-z_off
ctz(9)-518.2/12-z_off
ctz(10)-494.5/12-z_off
ctz(11)-476.2/12-z_off
ctz(12)-447.4/12-z_off
ctz(13)-407.1/12-z_off
ctz(14)-382.1/12-z_off
ctz(15)-335/12-z_off
ctz(16)-281/12-z_off
ctz(17)-236.5/12-z_off
ctz(18)-186.8/12-z_off
ctz(19)-145.5/12-z_off
ctz(20)-70/12-z_off
ctz(21)-(c_Floor+24)/12-z_off
ctz(22)-C_Floor/12-z_off
ctz(23)-C_Floor/12-z_off
ctz(24)-C_Floor/12-z_off
ctz(25)-C_Floor/12-z_off
ctz(26)-C_Floor/12-z_off
ctz(27)-C_Floor/12-z_off
ctz(28)-C_Floor/12-z_off
ctz(29)-C_Floor/12-z_off
ctz(30)-C_Floor/12-z_off
ctz(31)-C_Floor/12-z_off
ctz(32)-C_Floor/12-z_off
ctz(33)-C_Floor/12-z_off
ctz(34)-C_Floor/12-z_off

ptx(1)-0
ptx(2)-44.719/12
ptx(3)-89.87/12
ptx(4)-120/12
ptx(5)-151.97/12
ptx(6)-210.05/12
ptx(7)-237.53/12
ptx(8)-304.42/12
ptx(9)-333.05/12
ptx(10)-390.22/12
ptx(11)-422.26/12
ptx(12)-431.63/12
ptx(13)-450/12
ptx(14)-450/12
ptx(15)-450/12
ptx(16)-450/12
ptx(17)-450/12
ptx(18)-450/12
ptx(19)-450/12
ptx(20)-450/12
ptx(21)-450/12
ptx(22)-450/12
ptx(23)-450/12
ptx(24)-450/12
ptx(25)-450/12
ptx(26)-446.49/12
ptx(27)-438/12
ptx(28)-410/12
ptx(29)-358/12
ptx(30)-277.7/12
ptx(31)-218.5/12
ptx(32)-180/12
ptx(33)-129.9/12
```

```
ptx(34)–95.7/12
ptx(35)–36/12
ptx(36)–0

ptz(1)–561.77/12-z_off
ptz(2)–561.77/12-z_off
ptz(3)–558.37/12-z_off
ptz(4)–555.83/12-z_off
ptz(5)–552.29/12-z_off
ptz(6)–543.4/12-z_off
ptz(7)–537.96/12-z_off
ptz(8)–520.72/12-z_off
Ptz(9)–511.17/12-z_off
ptz(10)–486.37/12-z_off
ptz(11)–467.14/12-z_off
ptz(12)–460.2/12-z_off
ptz(13)–432.3125/12-z_off
ptz(14)–387.5/12-z_off
ptz(15)–353/12-z_off
ptz(16)–317.5/12-z_off
ptz(17)–282/12-z_off
ptz(18)–245.5/12-z_off
ptz(19)–214.6/12-z_off
ptz(20)–183.7/12-z_off
ptz(21)–152.8/12-z_off
ptz(22)–116/12-z_off
ptz(23)–80/12-z_off
ptz(24)–45/12-z_off
ptz(25)–20/12-z_off
ptz(26)–11.51/12-z_off
ptz(27)–8/12-z_off
ptz(28)–8/12-z_off
ptz(29)–8/12-z_off
ptz(30)–8/12-z_off
ptz(31)–8/12-z_off
ptz(32)–8/12-z_off
ptz(33)–8/12-z_off
ptz(34)–8/12-z_off
ptz(35)–8/12-z_off
ptz(36)–8/12-z_off
```

Tank-Mesh-1.txt

```
et,1,shell143          ! SHELL143 Elements for
Concrete Tank
keyopt,1,3,2
keyopt,1,5,1


csys,1                 ! Cylindrical Coordinates
/COM - Create KeyPoints for concrete tank
*do,i,1,ct_kps,1
k,i,ctx(i),0,ctz(i)
*enddo

/COM - Create lines from top of tank to bottom
of wall
*do,i,1,bm_kp-1,1
l,i,i+1
*enddo

/COM - Create lines from edge of foundation to
center
/COM - Wall and Foundation do not have common
lines
*do,i,bm_kp+1,ct_kps-1,1
l,i,i+1
*enddo
/COM - Create Areas for tank dome and walls
lsel,s,line,,1,bm_kp-1
arotat,all,,,,,,1,ct_kps,180,2

/COM - Create areas for tank foundation/floor
lsel,s,line,,bm_kp,ct_kps-2
arotat,all,,,,,,1,ct_kps,180,2

/COM - Assign Material and Real Properties to
areas
csys,1
*do,i,1,bm_kp-1,1
asel,s,loc,x,ctx(i),ctx(i+1)
asel,r,loc,z,ctz(i),ctz(i+1)
aatt,i,i,1
*enddo

asel,s,area,,1,2*(bm_kp-1)
CM,ctank-u,area

*do,i,bm_kp,ct_kps-2,1
asel,s,area,,bm_kp-1+i
asel,a,area,,ct_kps-2+i
aatt,i,i,1
*enddo

/COM - Create Elements
/COM - Elements at dome apex
esize,7                         ! Define element
maximum size
asel,s,loc,x,ctx(1),ctx(2)      ! Select area at
top
asel,r,loc,z,ctz(1),ctz(2)
lsla                            ! Select lines
from areas
lsel,r,loc,x,ctx(2)             ! Select line at a
radius of CTX(2)
lesize,all,,arcsize             ! Divide line to
match tank slices
lsla
lsel,u,loc,x,ctx(2)             ! Select only
interior lines
lesize,all,,,midsize            ! Define element
resolution
amesh,all                       ! Mesh area

/COM - Elements in dome and wall
*do,i,2,bm_kp-1,1
asel,s,loc,x,ctx(i),ctx(i+1)
asel,r,loc,z,ctz(i),ctz(i+1)
lsla
lsel,s,loc,x,ctx(i),ctx(i+1)
lsel,r,loc,z,ctz(i),ctz(i+1)
lesize,all,,arcsize
amesh,all
*enddo
cm,conc-dome_wall-n,node
cm,conc-dome_wall-e,elem

esel,none
nsel,none
*do,i,bm_kp+1,ct_kps-2,1
asel,s,area,,bm_kp-2+i
asel,a,area,,ct_kps-3+i
lsla
lsel,s,loc,x,ctx(i),ctx(i+1)
lsel,r,loc,z,ctz(i),ctz(i+1)
lesize,all,,arcsize
amesh,all
*enddo
```

```
/COM - Elements at floor center
asel,s,loc,x,ctx(ct_kps-1),ctx(ct_kps)
lsla
lsel,r,loc,x,ctx(ct_kps-1)
lesize,all,,arcsize
lsla
lsel,u,loc,x,ctx(ct_kps-1)
lesize,all,,,midsize
amesh,all
cm,conc-slab,node
cm,conc-floor-e,elem
allsel
cm,conc-tank,elem
cm,conc-tank-a,area

/COM - Create Component for Concrete Wall/Floor
Interface nodes
nsel,s,loc,z,ctz(bm_kp)
nsel,r,loc,x,ctx(bm_kp)
cm,Wall-int,node

allsel
*get,KMAXct,KP,0,num,max      ! Get Maximum
Keypoint Number
*get,LMAXct,LINE,0,num,max    ! Get Maximum Line
Number
*get,AMAXct,AREA,0,num,max    ! Get Maximum Area
Number
```

Primary-Props-AY-Uniform.txt

```
/COM - Material Definitions
/COM - Material 101, Tank Steel
mp,ex,101,4248000000
mp,nuxy,101,0.30
mp,dens,101,490/(1000*g)
mp,damp,101,0.04/df

/COM - Material 102, Tank Steel
mp,ex,102,4248000000
mp,nuxy,102,0.30
mp,dens,102,490/(1000*g)
mp,damp,102,0.04/df

/COM - Material 103, Tank Steel
mp,ex,103,4248000000
mp,nuxy,103,0.30
mp,dens,103,490/(1000*g)
mp,damp,103,0.04/df

/COM - Material 104, Tank Steel
mp,ex,104,4248000000
mp,nuxy,104,0.30
mp,dens,104,490/(1000*g)
mp,damp,104,0.04/df

/COM - Material  105, Tank Steel
mp,ex,105,4248000000
mp,nuxy,105,0.30
mp,dens,105,490/(1000*g)
mp,damp,105,0.04/df

/COM - Material 106, Tank Steel
mp,ex,106,4248000000
mp,nuxy,106,0.30
mp,dens,106,490/(1000*g)
mp,damp,106,0.04/df

/COM - Material 107, Tank Steel
mp,ex,107,4248000000
mp,nuxy,107,0.30
mp,dens,107,490/(1000*g)
mp,damp,107,0.04/df

/COM - Material 108, Tank Steel
mp,ex,108,4248000000
mp,nuxy,108,0.30
mp,dens,108,490/(1000*g)
mp,damp,108,0.04/df

/COM - Material 109, Tank Steel
mp,ex,109,4248000000
mp,nuxy,109,0.30
mp,dens,109,490/(1000*g)
mp,damp,109,0.04/df

/COM - Material,110, Tank Steel
mp,ex,110,4248000000
mp,nuxy,110,0.30
mp,dens,110,490/(1000*g)
mp,damp,110,0.04/df

/COM - Material,111, Tank Steel
mp,ex,111,4248000000
mp,nuxy,111,0.30
mp,dens,111,490/(1000*g)
mp,damp,111,0.04/df

/COM - Material,112, Tank Steel
mp,ex,112,4248000
mp,nuxy,112,0.30
mp,dens,112,490/(1000*g)
mp,damp,112,0.04/df

/COM - Material,113, Tank Steel
mp,ex,113,4248000
mp,nuxy,113,0.30
mp,dens,113,490/(1000*g)
mp,damp,113,0.04/df

/COM - Material,114, Tank Steel
mp,ex,114,4248000
mp,nuxy,114,0.30
mp,dens,114,490/(1000*g)
mp,damp,114,0.04/df

/COM - Material,115, Tank Steel
mp,ex,115,4248000
mp,nuxy,115,0.30
mp,dens,115,490/(1000*g)
mp,damp,115,0.04/df

/COM - Material,116, Tank Steel
mp,ex,116,4248000
mp,nuxy,116,0.30
mp,dens,116,490/(1000*g)
mp,damp,116,0.04/df

/COM - Material,117, Tank Steel
mp,ex,117,4248000
mp,nuxy,117,0.30
mp,dens,117,490/(1000*g)
mp,damp,117,0.04/df

/COM - Material,118, Tank Steel
mp,ex,118,4248000
mp,nuxy,118,0.30
```

```
mp,dens,118,490/(1000*g)
mp,damp,118,0.04/df

/COM - Material,119, Tank Steel
mp,ex,119,4248000
mp,nuxy,119,0.30
mp,dens,119,490/(1000*g)
mp,damp,119,0.04/df

/COM - Material,120, Tank Steel
mp,ex,120,4248000
mp,nuxy,120,0.30
mp,dens,120,490/(1000*g)
mp,damp,120,0.04/df

/COM - Material,121, Tank Steel
mp,ex,121,4248000
mp,nuxy,121,0.30
mp,dens,121,490/(1000*g)
mp,damp,121,0.04/df

/COM - Material,122, Tank Steel
mp,ex,122,4248000
mp,nuxy,122,0.30
mp,dens,122,490/(1000*g)
mp,damp,122,0.03/df

/COM - Material,123, Tank Steel
mp,ex,123,4248000
mp,nuxy,123,0.30
mp,dens,123,490/(1000*g)
mp,damp,123,0.04/df

/COM - Material,124, Tank Steel
mp,ex,124,4248000
mp,nuxy,124,0.30
mp,dens,124,490/(1000*g)
mp,damp,124,0.04/df

/COM - Material,125, Tank Steel
mp,ex,125,4248000
mp,nuxy,125,0.30
mp,dens,125,490/(1000*g)
mp,damp,125,0.04/df

/COM - Material,126, Tank Steel
mp,ex,126,4248000
mp,nuxy,126,0.30
mp,dens,126,490/(1000*g)
mp,damp,126,0.04/df

/COM - Material,127, Tank Steel
mp,ex,127,4248000
mp,nuxy,127,0.30
mp,dens,127,490/(1000*g)
mp,damp,127,0.04/df

/COM - Material,128, Tank Steel
mp,ex,128,4248000
mp,nuxy,128,0.30
mp,dens,128,490/(1000*g)
mp,damp,128,0.04/df

/COM - Material,129, Tank Steel
mp,ex,129,4248000
mp,nuxy,129,0.30
mp,dens,129,490/(1000*g)
mp,damp,129,0.04/df

/COM - Material,130, Tank Steel
mp,ex,130,4248000
mp,nuxy,130,0.30
mp,dens,130,490/(1000*g)
mp,damp,130,0.04/df

/COM - Material,131, Tank Steel
mp,ex,131,4248000
mp,nuxy,131,0.30
mp,dens,131,490/(1000*g)
mp,damp,131,0.04/df

/COM - Material,132, Tank Steel
mp,ex,132,4248000
mp,nuxy,132,0.30
mp,dens,132,490/(1000*g)
mp,damp,132,0.04/df

/COM - Material,133, Tank Steel
mp,ex,133,4248000
mp,nuxy,133,0.30
mp,dens,133,490/(1000*g)
mp,damp,133,0.04/df

/COM - Material,134, Tank Steel
mp,ex,134,4248000
mp,nuxy,134,0.30
mp,dens,134,490/(1000*g)
mp,damp,134,0.04/df

/COM - Material,135, Tank Steel
mp,ex,135,4248000
mp,nuxy,135,0.30
mp,dens,135,490/(1000*g)
mp,damp,135,0.04 /df

r,101,1
r,102,1
r,103,1
r,104,1
r,105,1
r,106,1
r,107,1
r,108,1
r,109,1
r,110,1
r,111,1
r,112,0.65/12
r,113,0.65/12
r,114,0.65/12
r,115,0.65/12
r,116,0.65/12
r,117,0.65/12
r,118,0.65/12
r,119,0.65/12
r,120,0.65/12
r,121,0.65/12
r,122,0.65/12
r,123,0.65/12
r,124,0.65/12
r,125,0.65/12
r,126,0.65/12
r,127,0.65/12
r,128,0.65/12
r,129,0.65/12
r,130,0.65/12
r,131,0.65/12
r,132,0.65/12
r,133,0.65/12
r,134,0.65/12
r,135,0.65/12
```

Primary-Props-AY-Rigid.txt

```
/COM - Material Definitions
/COM - Material 101, Tank Steel
mp,ex,101,4248000000
mp,nuxy,101,0.30
mp,dens,101,490/(1000*g)
mp,damp,101,0.04/df

/COM - Material 102, Tank Steel
mp,ex,102,4248000000
mp,nuxy,102,0.30
mp,dens,102,490/(1000*g)
mp,damp,102,0.04/df

/COM - Material 103, Tank Steel
mp,ex,103,4248000000
mp,nuxy,103,0.30
mp,dens,103,490/(1000*g)
mp,damp,103,0.04/df

/COM - Material 104, Tank Steel
mp,ex,104,4248000000
mp,nuxy,104,0.30
mp,dens,104,490/(1000*g)
mp,damp,104,0.04/df

/COM - Material  105, Tank Steel
mp,ex,105,4248000000
mp,nuxy,105,0.30
mp,dens,105,490/(1000*g)
mp,damp,105,0.04/df

/COM - Material 106, Tank Steel
mp,ex,106,4248000000
mp,nuxy,106,0.30
mp,dens,106,490/(1000*g)
mp,damp,106,0.04/df

/COM - Material 107, Tank Steel
mp,ex,107,4248000000
mp,nuxy,107,0.30
mp,dens,107,490/(1000*g)
mp,damp,107,0.04/df

/COM - Material 108, Tank Steel
mp,ex,108,4248000000
mp,nuxy,108,0.30
mp,dens,108,490/(1000*g)
mp,damp,108,0.04/df

/COM - Material 109, Tank Steel
mp,ex,109,4248000000
mp,nuxy,109,0.30
mp,dens,109,490/(1000*g)
mp,damp,109,0.04/df

/COM - Material,110, Tank Steel
mp,ex,110,4248000000
mp,nuxy,110,0.30
mp,dens,110,490/(1000*g)
mp,damp,110,0.04/df

/COM - Material,111, Tank Steel
mp,ex,111,4248000000
mp,nuxy,111,0.30
mp,dens,111,490/(1000*g)
mp,damp,111,0.04/df

/COM - Material,112, Tank Steel
mp,ex,112,4248000000
mp,nuxy,112,0.30
mp,dens,112,490/(1000*g)
mp,damp,112,0.04/df

/COM - Material,113, Tank Steel
mp,ex,113,4248000000
mp,nuxy,113,0.30
mp,dens,113,490/(1000*g)
mp,damp,113,0.04/df

/COM - Material,114, Tank Steel
mp,ex,114,4248000000
mp,nuxy,114,0.30
mp,dens,114,490/(1000*g)
mp,damp,114,0.04/df

/COM - Material,115, Tank Steel
mp,ex,115,4248000000
mp,nuxy,115,0.30
mp,dens,115,490/(1000*g)
mp,damp,115,0.04/df

/COM - Material,116, Tank Steel
mp,ex,116,4248000000
mp,nuxy,116,0.30
mp,dens,116,490/(1000*g)
mp,damp,116,0.04/df

/COM - Material,117, Tank Steel
mp,ex,117,4248000000
mp,nuxy,117,0.30
mp,dens,117,490/(1000*g)
mp,damp,117,0.04/df

/COM - Material,118, Tank Steel
mp,ex,118,4248000000
mp,nuxy,118,0.30
mp,dens,118,490/(1000*g)
mp,damp,118,0.04/df

/COM - Material,119, Tank Steel
mp,ex,119,4248000000
mp,nuxy,119,0.30
mp,dens,119,490/(1000*g)
mp,damp,119,0.04/df

/COM - Material,120, Tank Steel
mp,ex,120,4248000000
mp,nuxy,120,0.30
mp,dens,120,490/(1000*g)
mp,damp,120,0.04/df

/COM - Material,121, Tank Steel
mp,ex,121,4248000000
mp,nuxy,121,0.30
mp,dens,121,490/(1000*g)
mp,damp,121,0.04/df

/COM - Material,122, Tank Steel
mp,ex,122,4248000000
mp,nuxy,122,0.30
mp,dens,122,490/(1000*g)
mp,damp,122,0.03/df

/COM - Material,123, Tank Steel
mp,ex,123,4248000000
mp,nuxy,123,0.30
mp,dens,123,490/(1000*g)
```

```
mp,damp,123,0.04/df

/COM - Material,124, Tank Steel
mp,ex,124,4248000000
mp,nuxy,124,0.30
mp,dens,124,490/(1000*g)
mp,damp,124,0.04/df

/COM - Material,125, Tank Steel
mp,ex,125,4248000000
mp,nuxy,125,0.30
mp,dens,125,490/(1000*g)
mp,damp,125,0.04/df

/COM - Material,126, Tank Steel
mp,ex,126,4248000000
mp,nuxy,126,0.30
mp,dens,126,490/(1000*g)
mp,damp,126,0.04/df

/COM - Material,127, Tank Steel
mp,ex,127,4248000000
mp,nuxy,127,0.30
mp,dens,127,490/(1000*g)
mp,damp,127,0.04/df

/COM - Material,128, Tank Steel
mp,ex,128,4248000000
mp,nuxy,128,0.30
mp,dens,128,490/(1000*g)
mp,damp,128,0.04/df

/COM - Material,129, Tank Steel
mp,ex,129,4248000000
mp,nuxy,129,0.30
mp,dens,129,490/(1000*g)
mp,damp,129,0.04/df

/COM - Material,130, Tank Steel
mp,ex,130,4248000000
mp,nuxy,130,0.30
mp,dens,130,490/(1000*g)
mp,damp,130,0.04/df

/COM - Material,131, Tank Steel
mp,ex,131,4248000000
mp,nuxy,131,0.30
mp,dens,131,490/(1000*g)
mp,damp,131,0.04/df

/COM - Material,132, Tank Steel
mp,ex,132,4248000000
mp,nuxy,132,0.30
mp,dens,132,490/(1000*g)
mp,damp,132,0.04/df

/COM - Material,133, Tank Steel
mp,ex,133,4248000000
mp,nuxy,133,0.30
mp,dens,133,490/(1000*g)
mp,damp,133,0.04/df

/COM - Material,134, Tank Steel
mp,ex,134,4248000000
mp,nuxy,134,0.30
mp,dens,134,490/(1000*g)
mp,damp,134,0.04/df

/COM - Material,135, Tank Steel
mp,ex,135,4248000000
mp,nuxy,135,0.30
mp,dens,135,490/(1000*g)
mp,damp,135,0.04 /df

r,101,1
r,102,1
r,103,1
r,104,1
r,105,1
r,106,1
r,107,1
r,108,1
r,109,1
r,110,1
r,111,1
r,112,1
r,113,1
r,114,1
r,115,1
r,116,1
r,117,1
r,118,1
r,119,1
r,120,1
r,121,1
r,122,1
r,123,1
r,124,1
r,125,1
r,126,1
r,127,1
r,128,1
r,129,1
r,130,1
r,131,1
r,132,1
r,133,1
r,134,1
r,135,1
```

Primary.txt

```
/COM - Create KeyPoints for primarytank
*do,i,1,pt_kps,1
k,kmaxct+i,ptx(i),0,ptz(i)
*enddo

/COM - Create lines for primary tank
*do,i,1,pt_kps-1,1
l,kmaxct+i,kmaxct+i+1
*enddo

/COM - Create Areas for primary tank
lsel,s,line,,LMAXct+1,LMAXct+pt_kps-1
arotat,all,,,,,,1,ct_kps,180,2

/COM - Assign Material and Real Properties to
primary tank areas
csys,1
*do,i,1,pt_kps-1,1
asel,s,area,,AMAXct+i
asel,a,area,,AMAXct+pt_kps-1+i
aatt,100+i,100+i,1
*enddo
allsel

/COM - Elements at tank Top center
asel,s,loc,x,ptx(1),ptx(2)
asel,r,loc,z,ptz(1),ptz(2)
lsla
```

```
lsel,r,loc,x,ptx(2)
lesize,all,,arcsize
lsla
lsel,u,loc,x,ptx(2)
lesize,all,,,midsize
amesh,all

/COM - Elements in primary tank
*do,i,2,pt_kps-2,1
asel,s,area,,AMAXct+i
asel,a,area,,AMAXct+pt_kps-1+i
lsla
lsel,s,loc,x,ptx(i),ptx(i+1)
lsel,r,loc,z,ptz(i),ptz(i+1)
lesize,all,,arcsize
amesh,all
*enddo

/COM - Elements at tank floor center
asel,s,loc,x,ptx(pt_kps-1),ptx(pt_kps)
asel,r,loc,z,ptz(pt_kps)
cm,a1,area
lsla
lsel,r,loc,x,ptx(pt_kps-1)
lesize,all,,arcsize
lsla
lsel,u,loc,x,ptx(pt_kps-1)
lesize,all,,,midsize
amesh,all
asel,r,loc,y,0,-90
cm,a1a,area                    ! Component for
mesh mapping
cmsel,s,a1
cmsel,u,a1a
cm,a1b,area                    ! Compoment for
mesh mapping
allsel
cmsel,u,conc-tank
*get,emax,elem,,num,maxd
enorm,emax
cm,primary-tank,elem

allsel
*get,KMAXpt,KP,0,num,max       ! Get maximum
Keypoint number
*get,LMAXpt,LINE,0,num,max     ! Get maximum Line
Number
*get,AMAXpt,AREA,0,num,max     ! Get maximum Area
Number
```

Insulate.txt

```
et,2,solid45   ! SOLID45 elements for insulating
concrete

/COM - Key Points for Insulating Concrete
*do,i,0,tw,1
k,kmaxpt+1+i,ptx(pt_kps-i),0,ptz(pt_kps-i)   !
Match Keypoint to Primary Tank
k,kmaxpt+2+tw+i,ctx(ct_kps-i),0,ctz(ct_kps-i)
        ! Match Keypoint to Concrete Tank
*enddo

/COM - Areas for Insulating Concrete
*do,i,1,tw,1
a,kmaxpt+i,kmaxpt+tw+1+i,kmaxpt+tw+2+i,kmaxpt+1+
i
*enddo

/COM - Assign Material Properties
*do,i,1,tw,1
asel,s,area,,amaxpt+i
aatt,50,i,2
*enddo

asel,s,area,,amaxpt+1,amaxpt+tw
vrotat,all,,,,,,1,ct_kps,180,2

type,2
/COM - Elements in insulating concrete
*do,i,2,tw,1
vsel,s,volu,,i
vsel,a,volu,,tw+i
aslv
lsla
lsel,r,loc,x,ctx(ct_kps-i),ctx(ct_kps-i-1)
lesize,all,,arcsize
vmesh,all
*enddo

/COM - Mesh center volume to match primary tank
vsel,s,volu,,1,tw+1,tw
aslv
asel,r,loc,z,ptz(pt_kps)
cm,a2,area
cmsel,a,a1
mshcopy,2,a1,a2
type,2
vsweep,all,,all

allsel
esel,s,type,,2
mpchg,50,all
cm,insul-conc,elem
cmsel,a,primary-tank
nsle
nsel,r,loc,z,ptz(pt_kps)
cm,primary-int,node
allsel
cmsel,s,conc-tank
esel,a,type,,2
nsle
nsel,r,loc,z,ctz(ct_kps)
nsel,r,loc,x,ctx(ct_kps-tw),ctx(ct_kps)

cm,insul-vol,volu
cm,insul-int,node

*get,KMAXic,KP,0,num,max       ! Get maximum
Keypoint Number
*get,LMAXic,LINE,0,num,max     ! Get maximum Line
Number
*get,AMAXic,AREA,0,num,max     ! Get maximum Area
Number
*get,VMAXic,VOLU,0,num,max     ! Get maximum
Volume Number

cmsel,s,insul-conc
nsle
nsel,r,loc,z,ptz(pt_kps)
nsel,r,loc,x,ptx(pt_kps-tw)
csys,1
!nrotat,all
allsel
```

Liner.txt

```
ksel,u,kp,,all                  ! Clear active
Keypoints
asel,u,area,,all                ! Clear active
Areas
vsel,u,volu,,all                ! Clear active
Volumes
ksel,s,kp,,1,ct_kps,ct_kps-1  ! Activate
Keypoints for axis of rotation
esel,u,elem,,all
lsel,u,line,,all

et,21,combin14,,1
et,22,combin14,,2
et,23,combin14,,3

r,201,1e8
r,202,1e8
r,203,1e8


r,51,0.25/12

cmsel,s,insul-vol
aslv
asel,r,loc,z,ctz(ct_kps)

type,1
real,51
amesh,all

k,kmaxic+1,ctx(bm_kp+3),0,ctz(bm_kp+3)
k,kmaxic+2,ctx(bm_kp)-1,0,ctz(bm_kp)
k,kmaxic+3,ctx(bm_kp)-0.2929,0,ctz(bm_kp)+0.2929
k,kmaxic+4,ctx(bm_kp),0,ctz(bm_kp)+1
k,kmaxic+5,ctx(bm_kp-1),0,ctz(bm_kp-1)
k,kmaxic+6,ctx(bm_kp-2),0,ctz(bm_kp-2)

l,kmaxic+1,kmaxic+2
l,kmaxic+2,kmaxic+3
l,kmaxic+3,kmaxic+4
l,kmaxic+4,kmaxic+5
l,kmaxic+5,kmaxic+6

arotat,all,,,,,,1,ct_kps,180,2
cm,liner-lines,line
aatt,101,51,1


lsel,r,loc,x,ctx(bm_kp)
lesize,all,,arcsize
cmsel,s,liner-lines
lsel,r,loc,x,ctx(bm_kp+3)
lesize,all,,arcsize
cmsel,s,liner-lines
lsel,r,loc,x,ctx(bm_kp)-1
lesize,all,,arcsize
cmsel,s,liner-lines
lsel,r,loc,x,ctx(bm_kp)-0.2929
lesize,all,,arcsize


amesh,all
nsle
nummrg,node

cm,liner,elem
nsle
nsel,r,loc,x,ctx(bm_kp+3),ctx(bm_kp)-1
cpint,uz,3.5
cmsel,s,liner
nsle
nsel,r,loc,z,ctz(bm_kp-1),ctz(bm_kp)+1
cpintf,ux,3
cpintf,uy,3

allsel
nsel,s,loc,x,ctx(bm_kp)
nsel,r,loc,z,ctz(bm_kp-2),ctz(bm_kp-1)
cm,liner-wall,node

esel,none

/COM - Merge liner and concrete wall
nummrg,node


allsel
*get,KMAX1,KP,0,num,max        ! Get maximum
Keypoint Number
*get,LMAX1,LINE,0,num,max      ! Get maximum Line
Number
*get,AMAX1,AREA,0,num,max      ! Get maximum Area
Number
*get,VMAX1,VOLU,0,num,max      ! Get maximum
Volume Number
```

Waste-Solid-AP.txt (452 in Level)

```
et,3,solid45   ! FLUID80 (3-D Non-Flowing Fluid
elements)
Wastet-12      ! Primary tank coordinate for top
of waste (460 in for AP Tanks)
Wasteb-27      ! Primary tank coordinate for
bottom of waste

mp,ex,201,2.592                        ! Bulk
Modulus - 300,000 psi
mp,ey,201,2.592
mp,ez,201,2.592
mp,prxy,201,0.49999
mp,pryz,201,0.49999
mp,prxz,201,0.49999
mp,gxy,201,0.116
mp,gyz,201,0.116
mp,gxz,201,0.116
mp,dens,201,1.83*62.4/(1000*g)        ! Waste
Density

ksel,u,kp,,all                 ! Clear active
Keypoints
asel,u,area,,all               ! Clear active
Areas
vsel,u,volu,,all               ! Clear active
Volumes
ksel,s,kp,,1,ct_kps,ct_kps-1  ! Activate
Keypoints for center of rotation

/COM - Create KeyPoints for waste in tank
*do,i,0,Wasteb-Wastet,1
                ! Cycle on vertical Keypoints
*do,j,0,tw-1
        ! Cycle on horizontal Keypoints
k,kmaxl+i*(tw+1)+j+1,ptx(pt_kps-
j),0,ptz(i+Wastet)
*enddo
```

```
k,kmaxl+i*(tw+1)+j+2,ptx(i+Wastet),0,ptz(i+Waste
t)      !
*enddo


/COM - Create Areas for waste in tank
*do,i,0,Wasteb-Wastet-1,1
*do,j,0,tw-1
a,kmaxl+i*(tw+1)+j+1,kmaxl+i*(tw+1)+j+2,kmaxl+(i
+1)*(tw+1)+j+2,kmaxl+(i+1)*(tw+1)+j+1
*enddo
*enddo



/COM - Create Volumes for Waste
vrotat,all,,,,,,1,ct_kps,180,2

/COM - Assign attributes
vatt,201,,3

wastevols=(tw)*(wasteb-wastet)
/COM - Elements in waste
*do,i,0,Wasteb-Wastet-1,1
*do,j,1,tw-1,1
vsel,s,volu,,vmaxl+i*tw+j+1
vsel,a,volu,,vmaxl+wastevols+i*tw+j+1
aslv
lsla
lsel,r,loc,x,ptx(pt_kps-j),ptx(i+Wastet)
lesize,all,,arcsize
vmesh,all
*enddo
*enddo

allsel
/COM - Mesh center column to match primary tank
center
asel,s,loc,x,ptx(pt_kps-1),ptx(pt_kps)
asel,r,loc,z,ptz(wastet)
asel,r,loc,y,0,-90
cm,a3a,area
cmsel,s,a3a
cmsel,a,a1a
mshcopy,2,a1a,a3a,,,,ptz(wastet)-ptz(wasteb)
allsel
asel,s,loc,x,ptx(pt_kps-1),ptx(pt_kps)
asel,r,loc,z,ptz(wastet)
cmsel,u,a3a
cm,a3b,area
cmsel,a,a1b
mshcopy,2,a1b,a3b,,,,ptz(wastet)-ptz(wasteb)
vsel,s,volu,,vmaxl+1,vmaxl+2*wastevols+1,tw
vsweep,all,,all
cmsel,u,a1b
cmsel,a,a3a
aclear,all


esel,s,type,,3
cm,waste,elem
nsle
cm,waste-n,node
/COM - Couple waste to primary tank
csys,1
allsel

!cmsel,s,waste
!cmsel,s,primary-tank                 ! Select
Primary tank elements
!cmsel,a,waste                        ! Select
Waste elements
!nsle
!nsel,r,loc,x,ptx(wasteb-2),ptx(wastet)      !
Select nodes at vertical interface
!nsel,r,loc,z,ptz(wasteb),ptz(wastet)
!cpintf,ux                            ! Couple
nodes radially
!cpintf,uy
!nsle
!nsel,r,loc,x,ptx(36),ptx(34)         ! Select
node at bottom interface
!nsel,a,loc,z,ptz(21)
!cpintf,uz                            ! Couple
nodes vertically
!allsel

et,44,targe170
et,45,conta173
et,46,targe170
et,47,conta173
r,800,,,1000
r,900,,,5
keyopt,45,12,4
cmsel,s,primary-tank
nsle
nsel,r,loc,z,ptz(14),ptz(36)
!nsel,u,loc,x,ptx(36),ptx(33)
esln,r
nsle
type,44
real,800
esurf
*get,emax,elem,,num,maxd
enorm,emax
cmsel,s,waste
nsle
csys,1
nsel,r,loc,x,ptx(15)
nsel,a,loc,x,ptx(26)
nsel,a,loc,z,ptz(36)
nsel,r,loc,z,ptz(14),ptz(36)
esln,r
type,45
esurf

cmsel,s,primary-tank
nsle
nsel,r,loc,z,ptz(10),ptz(14)
esln,r
nsle
type,46
real,900
esurf
cmsel,s,waste
nsle
nsel,r,loc,x,ptx(12),ptx(14)
nsel,r,loc,z,ptz(12),ptz(14)
esln,r
type,47
esurf
esel,s,type,,45,47,2
cm,waste-surf,elem


!cmsel,s,waste
!nsle
!nsel,r,loc,z,ptz(wastet)

allsel
```

```
*get,KMAXw,KP,0,num,max                    !
Get maximum Keypoint number
*get,LMAXw,LINE,0,num,max           ! Get
maximum Line number
*get,AMAXw,AREA,0,num,max           ! Get
maximum Area number
*get,VMAXw,VOLU,0,num,max           ! Get
maximum Volume number
```

Waste-Solid-AP.txt (460 in Level)

```
et,3,solid45   ! Solid45 Elements
Wastet=11      ! Primary tank coordinate for top
of waste (460 in for AP Tanks)
Wasteb=27      ! Primary tank coordinate for
bottom of waste

mp,ex,201,2.592                     ! Bulk
Modulus = 300,000 psi
mp,ey,201,2.592
mp,ez,201,2.592
mp,prxy,201,0.49999
mp,pryz,201,0.49999
mp,prxz,201,0.49999
mp,gxy,201,0.464
mp,gyz,201,0.464
mp,gxz,201,0.464
mp,dens,201,1.83*62.4/(1000*g)      ! Waste
Density

ksel,u,kp,,all               ! Clear active
Keypoints
asel,u,area,,all             ! Clear active
Areas
vsel,u,volu,,all             ! Clear active
Volumes
ksel,s,kp,,1,ct_kps,ct_kps-1  ! Activate
Keypoints for center of rotation

/COM - Create KeyPoints for waste in tank
*do,i,0,Wasteb-Wastet,1
               ! Cycle on vertical Keypoints
*do,j,0,tw-1
       ! Cycle on horizontal Keypoints
k,kmaxl+i*(tw+1)+j+1,ptx(pt_kps-
j),0,ptz(i+Wastet)
*enddo
k,kmaxl+i*(tw+1)+j+2,ptx(i+Wastet),0,ptz(i+Waste
t)      !
*enddo


/COM - Create Areas for waste in tank
*do,i,0,Wasteb-Wastet-1,1
*do,j,0,tw-1
a,kmaxl+i*(tw+1)+j+1,kmaxl+i*(tw+1)+j+2,kmaxl+(i
+1)*(tw+1)+j+2,kmaxl+(i+1)*(tw+1)+j+1
*enddo
*enddo



/COM - Create Volumes for Waste
vrotat,all,,,,,,1,ct_kps,180,2

/COM - Assign attributes
vatt,201,,3

wastevols=(tw)*(wasteb-wastet)
/COM - Elements in waste
*do,i,0,Wasteb-Wastet-1,1
*do,j,1,tw-1,1
vsel,s,volu,,vmaxl+i*tw+j+1
vsel,a,volu,,vmaxl+wastevols+i*tw+j+1
aslv
lsla
lsel,r,loc,x,ptx(pt_kps-j),ptx(i+Wastet)
lesize,all,,arcsize
vmesh,all
*enddo
*enddo

allsel
/COM - Mesh center column to match primary tank
center
asel,s,loc,x,ptx(pt_kps-1),ptx(pt_kps)
asel,r,loc,z,ptz(wastet)
asel,r,loc,y,0,-90
cm,a3a,area
cmsel,s,a3a
cmsel,a,a1a
mshcopy,2,a1a,a3a,,,,ptz(wastet)-ptz(wasteb)
allsel
asel,s,loc,x,ptx(pt_kps-1),ptx(pt_kps)
asel,r,loc,z,ptz(wastet)
cmsel,u,a3a
cm,a3b,area
cmsel,a,a1b
mshcopy,2,a1b,a3b,,,,ptz(wastet)-ptz(wasteb)
vsel,s,volu,,vmaxl+1,vmaxl+2*wastevols+1,tw
vsweep,all,,all
cmsel,u,a1b
cmsel,a,a3a
aclear,all


esel,s,type,,3
cm,waste,elem
nsle
cm,waste-n,node
/COM - Couple waste to primary tank
csys,1
allsel


et,44,targe170
et,45,conta173
r,800,,,1000
r,801,,,1000
r,802,,,1000
r,803,,,1000
r,804,,,1000
r,805,,,1000
r,806,,,1000
keyopt,45,12,4


! - Third Facet of Haunch
cmsel,s,primary-tank
nsle
nsel,r,loc,z,ptz(11),ptz(12)
nsel,r,loc,x,ptx(11),ptx(12)
esln,r,1
type,44
real,806
esurf
cmsel,s,waste
nsle
nsel,r,loc,z,ptz(11),ptz(12)
```

```
nsel,r,loc,x,ptx(11),ptx(12)
esln,r
type,45
esurf

! - Second Facet of Haunch
cmsel,s,primary-tank
nsle
nsel,r,loc,z,ptz(12),ptz(13)
nsel,r,loc,x,ptx(12),ptx(13)
esln,r,1
type,44
real,805
esurf
cmsel,s,waste
nsle
nsel,r,loc,z,ptz(12),ptz(13)
nsel,r,loc,x,ptx(12),ptx(13)
esln,r
type,45
esurf

! - First Facet of Haunch
cmsel,s,primary-tank
nsle
nsel,r,loc,z,ptz(13),ptz(14)
nsel,r,loc,x,ptx(13),ptx(14)
esln,r,1
type,44
real,804
esurf
cmsel,s,waste
nsle
nsel,r,loc,z,ptz(13),ptz(14)
nsel,r,loc,x,ptx(13),ptx(14)
esln,r
type,45
esurf

cmsel,s,primary-tank
nsle
nsel,r,loc,z,ptz(14),ptz(25)
esln,r,1
nsle
type,44
real,803
esurf
cmsel,s,waste
nsle
nsel,r,loc,z,ptz(14),ptz(25)
nsel,r,loc,x,ptx(14)
esln,r
type,45
esurf

! - Second Facet of Knuckle
cmsel,s,primary-tank
nsle
nsel,r,loc,z,ptz(25),ptz(26)
nsel,r,loc,x,ptx(25),ptx(26)
esln,r,1
type,44
real,802
esurf
cmsel,s,waste
nsle
nsel,r,loc,z,ptz(25),ptz(26)
nsel,r,loc,x,ptx(25),ptx(26)
esln,r
type,45
esurf

! - First Facet of Knuckle
cmsel,s,primary-tank
nsle
nsel,r,loc,z,ptz(26),ptz(27)
nsel,r,loc,x,ptx(26),ptx(27)
esln,r,1
type,44
real,801
esurf
cmsel,s,waste
nsle
nsel,r,loc,z,ptz(26),ptz(27)
nsel,r,loc,x,ptx(26),ptx(27)
esln,r
type,45
esurf

! - Bottom of Waste
cmsel,s,primary-tank
nsle
nsel,r,loc,z,ptz(36)
esln,r,1
type,44
real,800
esurf
cmsel,s,waste
nsle
nsel,r,loc,z,ptz(36)
esln,r
type,45
esurf

esel,s,type,,45
cm,waste-surf,elem

!cmsel,s,waste
!nsle
!nsel,r,loc,z,ptz(wastet)

allsel
*get,KMAXw,KP,0,num,max                    !
Get maximum Keypoint number
*get,LMAXw,LINE,0,num,max          ! Get
maximum Line number
*get,AMAXw,AREA,0,num,max          ! Get
maximum Area number
*get,VMAXw,VOLU,0,num,max          ! Get
maximum Volume number
```

Waste-Solid-AY.txt

```
et,3,solid45   ! FLUID80 (3-D Non-Flowing Fluid
elements)
Wastet=13      ! Primary tank coordinate for top
of waste (422 in for AY Tanks)
Wasteb=27      ! Primary tank coordinate for
bottom of waste

mp,ex,201,2.592                    ! Bulk
Modulus - 300,000 psi
mp,ey,201,2.592
```

```
mp,ez,201,2.592
mp,prxy,201,0.49999
mp,pryz,201,0.49999
mp,prxz,201,0.49999
mp,gxy,201,0.464
mp,gyz,201,0.464
mp,gxz,201,0.464
mp,dens,201,1.7*62.4/(1000*g) ! Waste Density

ksel,u,kp,,all                ! Clear active
Keypoints
asel,u,area,,all              ! Clear active
Areas
vsel,u,volu,,all              ! Clear active
Volumes
ksel,s,kp,,1,ct_kps,ct_kps-1  ! Activate
Keypoints for center of rotation

/COM - Create KeyPoints for waste in tank
*do,i,0,Wasteb-Wastet,1
               ! Cycle on vertical Keypoints
*do,j,0,tw-1
       ! Cycle on horizontal Keypoints
k,kmaxl+i*(tw+1)+j+1,ptx(pt_kps-
j),0,ptz(i+Wastet)
*enddo
k,kmaxl+i*(tw+1)+j+2,ptx(i+Wastet),0,ptz(i+Waste
t)      !
*enddo


/COM - Create Areas for waste in tank
*do,i,0,Wasteb-Wastet-1,1
*do,j,0,tw-1
a,kmaxl+i*(tw+1)+j+1,kmaxl+i*(tw+1)+j+2,kmaxl+(i
+1)*(tw+1)+j+2,kmaxl+(i+1)*(tw+1)+j+1
*enddo
*enddo



/COM - Create Volumes for Waste
vrotat,all,,,,,,1,ct_kps,180,2

/COM - Assign attributes
vatt,201,,3

wastevols=(tw)*(wasteb-wastet)
/COM - Elements in waste
*do,i,0,Wasteb-Wastet-1,1
*do,j,1,tw-1,1
vsel,s,volu,,vmaxl+i*tw+j+1
vsel,a,volu,,vmaxl+wastevols+i*tw+j+1
aslv
lsla
lsel,r,loc,x,ptx(pt_kps-j),ptx(i+Wastet)
lesize,all,,arcsize
vmesh,all
*enddo
*enddo

allsel
/COM - Mesh center column to match primary tank
center
asel,s,loc,x,ptx(pt_kps-1),ptx(pt_kps)
asel,r,loc,z,ptz(wastet)
asel,r,loc,y,0,-90
cm,a3a,area
cmsel,s,a3a
cmsel,a,a1a
mshcopy,2,a1a,a3a,,,,ptz(wastet)-ptz(wasteb)
allsel
asel,s,loc,x,ptx(pt_kps-1),ptx(pt_kps)
asel,r,loc,z,ptz(wastet)
cmsel,u,a3a
cm,a3b,area
cmsel,a,a1b
mshcopy,2,a1b,a3b,,,,ptz(wastet)-ptz(wasteb)
vsel,s,volu,,vmaxl+1,vmaxl+2*wastevols+1,tw
vsweep,all,,all
cmsel,u,a1b
cmsel,a,a3a
aclear,all


esel,s,type,,3
cm,waste,elem
nsle
cm,waste-n,node
/COM - Couple waste to primary tank
csys,1
allsel

!cmsel,s,waste
!cmsel,s,primary-tank                   ! Select
Primary tank elements
!cmsel,a,waste                          ! Select
Waste elements
!nsle
!nsel,r,loc,x,ptx(wasteb-2),ptx(wastet)      !
Select nodes at vertical interface
!nsel,r,loc,z,ptz(wasteb),ptz(wastet)
!cpintf,ux                              ! Couple
nodes radially
!cpintf,uy
!nsle
!nsel,r,loc,x,ptx(36),ptx(34)           ! Select
node at bottom interface
!nsel,a,loc,z,ptz(21)
!cpintf,uz                              ! Couple
nodes vertically
!allsel

et,44,targe170
et,45,conta173
r,800,,,1000
!keyopt,45,2,3
!keyopt,45,5,3
!keyopt,45,9,1
keyopt,45,12,4
cmsel,s,primary-tank
nsle
nsel,r,loc,z,ptz(14),ptz(36)
!nsel,u,loc,x,ptx(36),ptx(33)
esln,r
nsle
type,44
real,800
esurf
*get,emax,elem,,num,maxd
enorm,emax
cmsel,s,waste
nsle
nsel,r,loc,x,ptx(11),ptx(15)
nsel,a,loc,z,ptz(36)
!nsel,u,loc,x,ptx(36),ptx(34)
esln,r
type,45
esurf
esel,s,type,,45
```

```
cm,waste-surf,elem


!cmsel,s,waste
!nsle
!nsel,r,loc,z,ptz(wastet)

allsel
*get,KMAXw,KP,0,num,max                      !
Get maximum Keypoint number
*get,LMAXw,LINE,0,num,max            ! Get
maximum Line number
*get,AMAXw,AREA,0,num,max            ! Get
maximum Area number
*get,VMAXw,VOLU,0,num,max            ! Get
maximum Volume number
```

Bolts-NS.txt

```
pi=acos(-1)                   ! Define PI

!ET,4,BEAM44           ! Rigid Links
!KEYOPT,4,8,111
et,4,BEAM4
keyopt,4,6,1


/COM - Create Rigid Links for J-Bolts
nj_bolt=11

mp,ex,401,4176000000
mp,nuxy,401,0.30
mp,dens,401,0
r,401,0.055785,0.000886,0.000886,0.25,0.25
rmore,,1e-3,1.111,1.111
r,402,0.022496,0.000357,0.000357,0.25,0.25
rmore,,1e-3,1.111,1.111
r,403,0.036272,0.000576.0.000576,0.25,0.25
rmore,,1e-3,1.111,1.111
r,404,0.041997,0.000667,0.000667,0.25,0.25
rmore,,1e-3,1.111,1.111
r,405,0.080635,0.001281,0.001281,0.25,0.25
rmore,,1e-3,1.111,1.111
r,406,0.135051,0.001564,0.001564,0.25,0.25
rmore,,1e-3,1.111,1.111
r,407,0.098452,0.002146,0.002164,0.25,0.25
rmore,,1e-3,1.111,1.111
r,408,0.135051,0.002626,0.002626,0.25,0.25
rmore,,1e-3,1.111,1.111
r,409,0.178714,0.002840,0.002840,0.25,0.25
rmore,,1e-3,1.111,1.111
r,410,0.219326,0.003485,0.003485,0.25,0.25
rmore,,1e-3,1.111,1.111
r,411,0.221402,0.007910,0.007910,0.25,0.25
rmore,,1e-3,1.111,1.111

r,421,0.055785/2,0.000886/2,0.000886/2,0.25,0.25
rmore,,1e-3,1.111,1.111
r,422,0.022496/2,0.000357/2,0.000357/2,0.25,0.25
rmore,,1e-3,1.111,1.111
r,423,0.036272/2,0.000576/2,0.000576/2,0.25,0.25
rmore,,1e-3,1.111,1.111
r,424,0.041997/2,0.000667/2,0.000667/2,0.25,0.25
rmore,,1e-3,1.111,1.111
r,425,0.080635/2,0.001281/2,0.001281/2,0.25,0.25
rmore,,1e-3,1.111,1.111
r,426,0.098452/2,0.001564/2,0.002146/2,0.25,0.25
rmore,,1e-3,1.111,1.111
r,427,0.135051/2,0.002146/2,0.002146/2,0.25,0.25
rmore,,1e-3,1.111,1.111
r,428,0.165237/2,0.002626/2,0.002626/2,0.25,0.25
rmore,,1e-3,1.111,1.111
r,429,0.178714/2,0.002840/2,0.002840/2,0.25,0.25
rmore,,1e-3,1.111,1.111
r,430,0.219326/2,0.003485/2,0.003485/2,0.25,0.25
rmore,,1e-3,1.111,1.111
r,431,0.221402/2,0.00791/2,0.00791/2,0.25,0.25
rmore,,1e-3,1.111,1.111

/COM - Create link at top center of tanks
type,4
mat,401
real,401

nsel,s,loc,x,0                       ! Select
nodes on model origin
nsel,r,loc,z,ptz(1),ctz(1)           ! Reselect
nodes on concrete and primary tanks
!nsel,u,node,,1
eintf,100                            ! Place
link at dome center

nsel,s,loc,x,0                       ! Select
nodes on model origin
nsel,r,loc,z,ctz(1)                  ! Reselect
nodes on concrete and free end of j-bolt
cpint,ux                             ! Create
couples between j-bolt and concrete tank
(eliminate moment transfer to j-bolts)
cpint,uy
cpint,uz

csys,1
/COM - Create links for J-Bolts
*do,i,2,nj_bolt                              !
Cycle by radius
REAL,400+i
*do,j,1,180/arcsize-1                ! Cycle by
model slice
angley=-j*arcsize                    ! Define
angle for node selection
nsel,s,loc,x,ctx(i)
nsel,a,loc,x,ptx(i)                  ! Select
nodes at radius
nsel,r,loc,y,angley                  ! Reselect
nodes at angle "anlgey"
cmsel,u,waste-n
eintf,100                            ! Create
rigid link
*enddo
real,420+i
nsel,s,loc,x,ctx(i)
nsel,a,loc,x,ptx(i)                  ! Select
nodes at radius
nsel,r,loc,y,0                       ! Reselect
nodes at angle 0
cmsel,u,waste-n
eintf,100                            ! Create
rigid link
nsel,s,loc,x,ctx(i)
nsel,a,loc,x,ptx(i)                  ! Select
nodes at radius
nsel,r,loc,y,180                     ! Reselect
nodes at angle 180
cmsel,u,waste-n
eintf,100                            ! Create
rigid link

*enddo
```

```
esel,s,type,,4
cm,j_bolts,elem                                  !
Create component for J-Bolt rigid links
allsel

*get,KMAXjb,KP,0,num,max      ! Get maximum
keypoint number
*get,LMAXjb,LINE,0,num,max    ! Get maximum line
number
*get,AMAXjb,AREA,0,num,max    ! Get maximum area
number
*get,VMAXjb,volu,0,num,max    ! Get maximum
volume number
```

Near-Soil-1.txt

```
et,8,solid45                          ! Use
Element SOLID45 for Near Soil Elements
/input,soil-prop-mean-geo,txt         ! Read
Soil Properties

ksel,u,kp,,1,kmaxjb                   ! Unselect
existing Keypoints
asel,u,area,,1,amaxjb                 ! Unselect
existing Area
lsel,u,line,,1,lmaxjb                 ! Unselect
existing Lines
vsel,u,volu,,1,vmaxw                  ! Unselect
existing Volumes

/COM - Create Keypoints to match concrete tank
profile
*do,i,1,bm_kp
k,kmaxjb+i,ctx(i),0,ctz(i)
*enddo

/COM - Create Keypoints above top of tank
k,kmaxjb+bm_kp+1,0,0,0        ! Keypoint at
origin (surface)
k,kmaxjb+bm_kp+2,0,0,soilz(2) ! Keypoint at to
divide soil above tank
*get,KMAXtemp1,KP,0,num,max   ! Get maximum
keypoint number for counter

/COM - Create Keypoints at outside of excavated
soil
*do,i,1,tanksoil
k,kmaxtemp1+i,soilx(i),0,soilz(i)
*enddo
*get,KMAXtemp2,KP,0,num,max                     !
Get maximum keypoint number for counter

/COM - Create additional keypoint in soil above
tank
k,kmaxtemp2+1,ctx(2),0,soilz(1)
k,kmaxtemp2+2,ctx(9),0,soilz(1)
k,kmaxtemp2+3,ctx(12),0,soilz(1)
k,kmaxtemp2+4,ctx(2),0,soilz(2)
k,kmaxtemp2+5,ctx(9),0,soilz(2)
k,kmaxtemp2+6,ctx(12),0,soilz(2)
k,kmaxtemp2+7,ctx(12),0,soilz(3)
k,kmaxtemp2+8,ctx(bm_kp+1),0,ctz(bm_kp+1)

a,kmaxtemp2+1,kmaxtemp2+2,kmaxtemp2+5,kmaxtemp2+
4
a,kmaxtemp2+2,kmaxtemp2+3,kmaxtemp2+6,kmaxtemp2+
5
a,kmaxtemp2+3,kmaxtemp1+1,kmaxtemp1+2,kmaxtemp2+
6
a,kmaxtemp2+4,kmaxtemp2+5,kmaxjb+9,kmaxjb+8,kmax
jb+7,kmaxjb+6,kmaxjb+5,kmaxjb+4,kmaxjb+3,kmaxjb+
2!a,740,741,712,711,710,709,708,707,706,705
a,kmaxtemp2+5,kmaxtemp2+6,kmaxtemp2+7,kmaxjb+12,
kmaxjb+11,kmaxjb+10,kmaxjb+9
a,kmaxtemp2+6,kmaxtemp1+2,kmaxtemp1+3,kmaxtemp2+
7
a,kmaxtemp2+7,kmaxtemp1+3,kmaxtemp1+4,kmaxjb+12
a,kmaxjb+12,kmaxtemp1+4,kmaxtemp1+5,kmaxjb+14,km
axjb+13
a,kmaxjb+14,kmaxtemp1+5,kmaxtemp1+6,kmaxjb+16,km
axjb+15
a,kmaxjb+16,kmaxtemp1+6,kmaxtemp1+7,kmaxjb+18,km
axjb+17
a,kmaxjb+18,kmaxtemp1+7,kmaxtemp1+8,kmaxjb+20,km
axjb+19
a,kmaxjb+20,kmaxtemp1+8,kmaxtemp1+9,kmaxtemp2+8,
kmaxjb+22,kmaxjb+21

cm,top-soil-area,area
lsla
cm,top-soil,line
type,1
real,1


/COM - Define line divisions to control meshing
lsel,s,loc,z,soilz(1),soilz(2)
lsel,r,loc,x,ctx(3),ctx(8)
lesize,all,,,7               ! soil above tank
top, match tank meshing
lsel,s,loc,z,soilz(1),soilz(2)
lsel,r,loc,x,ctx(10),ctx(11)
lesize,all,,,3               ! soil above tank
top, match tank meshing
cmsel,s,top-soil             ! Reselect lines
in near soil
lsel,r,loc,x,ctx(2)
lesize,all,,,1               ! Control vertical
element size, above tank
cmsel,s,top-soil
lsel,s,loc,x,ctx(9)
lesize,all,,,1               ! Control vertical
element size, above tank
cmsel,s,top-soil
lsel,r,loc,x,ctx(12)
lesize,all,,,1               ! Control vertical
element size, above tank
cmsel,s,top-soil
lsel,r,loc,z,ctz(2),ctz(12)
lsel,r,loc,x,ctx(2),ctx(12)
lesize,all,,,1               ! Control vertical
element size, outside excavation mesh
lsel,s,line,,lmaxjb+8,lmaxjb+10,2
lsel,a,line,,lmaxjb+26,lmaxjb+28,2
lsel,a,line,,lmaxjb+30,lmaxjb+42,4
lesize,all,,,5               ! Control
horizontal meshing in soil
lsel,s,line,,lmaxjb+9
lsel,a,line,,lmaxjb+25,lmaxjb+27,2
lsel,a,line,,lmaxjb+29,lmaxjb+45,4
lsel,a,line,,lmaxjb+6
lsel,a,line,,lmaxjb+20,lmaxjb+21
lsel,a,line,,lmaxjb+32,lmaxjb+44,4
lsel,a,line,,lmaxjb+31,lmaxjb+43,4
lsel,a,line,,lmaxjb+47,lmaxjb+49
lesize,all,,,1               ! Control meshing
to match tank
```

```
lsel,s,line,,lmaxjb+46
lesize,all,,,4                ! Control mesh
size at bottom of excavated soil

cmsel,s,top-soil-area

amesh,all                     ! Mesh area to
develop pattern for volume meshing

type,8
ksel,a,kp,,1                  ! Select Keypoint
for rotation axis
ksel,a,kp,,ct_kps             ! Select Keypoint
for rotation axis
vrotat,all,,,,,,1,ct_kps,180,2       ! Generate
Volumes for excavated soil
lsla
lsel,r,loc,x,ctx(2)
lesize,all,,arcsize           ! Define meshing
for slices
lsla
lsel,r,loc,x,ctx(9)
lesize,all,,arcsize           ! Define meshing
for slices
lsla
lsel,r,loc,x,ctx(12)
lesize,all,,arcsize           ! Define meshing
for slices
vsweep,all                    ! Sweep pattern
into volume
aclear,all                    ! Delete elements
used for sweep
cm,top-soil-vol,volu

*get,VMAXtemp,VOLU,0,num,max
/COM - Generate element above top center of tank
asel,u,area,,all
vsel,u,volu,,all
a,kmaxjb+bm_kp+1,kmaxtemp2+1,kmaxtemp2+4,kmaxjb+
bm_kp+2
a,kmaxjb+bm_kp+2,kmaxtemp2+4,kmaxjb+2,kmaxjb+1
vrotat,all,,,,,,1,ct_kps,180,2
vsel,s,volu,,vmaxtemp+1,vmaxtemp+3,2
vatt,801,,8                          ! Assign
material properties
vsel,s,volu,,vmaxtemp+2,vmaxtemp+4,2
vatt,802,,8                          ! Assign
material properties
vsel,s,volu,,vmaxtemp+1,vmaxtemp+4
allsel
asel,s,loc,z,ctz(1),ctz(2)
type,1
asel,r,loc,x,0,4
asel,r,loc,z,ctz(1),ctz(2)
cmsel,u,conc-tank-a
*get,atemp,area,,num,max
*get,atemp1,area,,num,min
asel,a,area,,1,22,21
mshcopy,2,1,atemp1            ! copy mesh top
match top of concrete tank
mshcopy,2,22,atemp            ! copy mesh top
match top of concrete tank
vsel,s,volu,,vmaxtemp+1,vmaxtemp+4
vsweep,all                           ! Generate
elements by sweeping area

/COM - Assign soil properties by layer
*do,i,1,tanksoil-1
cmsel,s,top-soil-vol
vsel,r,loc,z,soilz(i),soilz(i+1)
eslv
emodif,all,mat,800+i
esys,0
*enddo

cmsel,s,top-soil-vol
vsel,a,loc,z,soilz(1),ctz(2)
eslv
cm,excav-soil,elem
nsle
nummrg,node

/COM - Define component for excavated soil -
tank walls only
cmsel,s,excav-soil
nsle,s,1
nsel,r,loc,z,soilz(5),soilz(9)
esln,r,1
cm,excav-wall,elem


/COM - Define component for excavated soil -
tank dome only
cmsel,s,excav-soil
cmsel,u,excav-wall
cm,excav-dome,elem

csys,1
cmsel,s,excav-wall
nsle
nsel,r,loc,x,ctx(14)
cm,excav-wall-n,node

allsel
*get,KMAXns,KP,0,num,max       ! Get maximum
Keypoint number
*get,LMAXns,LINE,0,num,max     ! Get maximum line
number
*get,AMAXns,AREA,0,num,max     ! Get maximum Area
number
*get,VMAXns,volu,0,num,max     ! Get maximum
Volume number
```

Soil-Prop-Mean-Geo.txt

```
Tanksoil=9
deepsoil=20
soil_radius=320
mass=1e8

*dim,soilx,,30
*dim,soilz,,30


soilz(1)=0
soilz(2)=-5
soilz(3)=ctz(9)
soilz(4)=ctz(12)
soilz(5)=ctz(14)
soilz(6)=ctz(16)
soilz(7)=ctz(18)
soilz(8)=ctz(20)
soilz(9)=ctz(23)
soilz(10)=-73.5
soilz(11)=-90.5
soilz(12)=-106.5
soilz(13)=-123.5
soilz(14)=-139.5
soilz(15)=-156
```

```
soilz(16)=-178
soilz(17)=-200
soilz(18)=-222
soilz(19)=-244
soilz(20)=-266

soilx(9)=68
soilx(8)=soilx(9)-(soilz(9)-soilz(8))/1.5
soilx(7)=soilx(9)-(soilz(9)-soilz(7))/1.5
soilx(6)=soilx(9)-(soilz(9)-soilz(6))/1.5
soilx(5)=soilx(9)-(soilz(9)-soilz(5))/1.5
soilx(4)=soilx(9)-(soilz(9)-soilz(4))/1.5
soilx(3)=soilx(9)-(soilz(9)-soilz(3))/1.5
soilx(2)=soilx(9)-(soilz(9)-soilz(2))/1.5
soilx(1)=soilx(9)-(soilz(9)-soilz(1))/1.5


/COM Excavated Soil Properties

/COM - Material Definitions
/COM - Material 801, Soil     (Top Layer)
mp,ex,801,9958
mp,nuxy,801,0.27
mp,dens,801,125/(1000*g)
mp,damp,801,0.019/df

/COM - Material 802, Soil
mp,ex,802,8797
mp,nuxy,802,0.27
mp,dens,802,125/(1000*g)
mp,damp,802,0.035/df

/COM - Material 803, Soil
mp,ex,803,7845
mp,nuxy,803,0.27
mp,dens,803,125/(1000*g)
mp,damp,803,0.048/df

/COM - Material 804, Soil
mp,ex,804,8209
mp,nuxy,804,0.27
mp,dens,804,125/(1000*g)
mp,damp,804,0.039/df

/COM - Material 805, Soil
mp,ex,805,7634
mp,nuxy,805,0.27
mp,dens,805,125/(1000*g)
mp,damp,805,0.048/df

/COM - Material 806, Soil
mp,ex,806,7188
mp,nuxy,806,0.27
mp,dens,806,125/(1000*g)
mp,damp,806,0.055/df

/COM - Material 807, Soil
mp,ex,807,6933
mp,nuxy,807,0.27
mp,dens,807,125/(1000*g)
mp,damp,807,0.059/df

/COM - Material 808, Soil
mp,ex,808,7667
mp,nuxy,808,0.27
mp,dens,808,125/(1000*g)
mp,damp,808,0.045/df


/COM - Mean Soil Properties Geomatrix Soil Data

/COM - 19 Layer Mode
/COM - Material Definitions

/COM - Material 901, Soil     (Top Layer)
mp,ex,901,16423
mp,nuxy,901,0.24
mp,dens,901,110/(1000*g)
mp,damp,901,0.017/df

/COM - Material 902, Soil
mp,ex,902,15479
mp,nuxy,902,0.24
mp,dens,902,110/(1000*g)
mp,damp,902,0.025/df

/COM - Material 903, Soil
mp,ex,903,14481
mp,nuxy,903,0.24
mp,dens,903,110/(1000*g)
mp,damp,903,0.034/df

/COM - Material 904, Soil
mp,ex,904,14707
mp,nuxy,904,0.24
mp,dens,904,110/(1000*g)
mp,damp,904,0.028/df

/COM - Material 905, Soil
mp,ex,905,13625
mp,nuxy,905,0.19
mp,dens,905,110/(1000*g)
mp,damp,905,0.032/df

/COM - Material 906, Soil
mp,ex,906,15456
mp,nuxy,906,0.19
mp,dens,906,110/(1000*g)
mp,damp,906,0.033/df

/COM - Material 907, Soil
mp,ex,907,17532
mp,nuxy,907,0.19
mp,dens,907,110/(1000*g)
mp,damp,907,0.033/df

/COM - Material 908, Soil
mp,ex,908,20972
mp,nuxy,908,0.19
mp,dens,908,110/(1000*g)
mp,damp,908,0.025/df

/COM - Material 909, Soil
mp,ex,909,23447
mp,nuxy,909,0.19
mp,dens,909,110/(1000*g)
mp,damp,909,0.026/df

/COM - Material 910, Soil
mp,ex,910,23138
mp,nuxy,910,0.19
mp,dens,910,110/(1000*g)
mp,damp,910,0.027/df

/COM - Material 911, Soil
mp,ex,911,22753
mp,nuxy,911,0.19
mp,dens,911,110/(1000*g)
mp,damp,911,0.029/df

/COM - Material 912, Soil
```

```
mp,ex,912,22069
mp,nuxy,912,0.19
mp,dens,912,110/(1000*g)
mp,damp,912,0.033/df

/COM - Material 913, Soil
mp,ex,913,25780
mp,nuxy,913,0.19
mp,dens,913,110/(1000*g)
mp,damp,913,0.025/df

/COM - Material 914, Soil
mp,ex,914,25333
mp,nuxy,914,0.19
mp,dens,914,110/(1000*g)
mp,damp,914,0.027/df

/COM - Material 915, Soil
mp,ex,915,35501
mp,nuxy,915,0.28
mp,dens,915,120/(1000*g)
mp,damp,915,0.022/df

/COM - Material 916, Soil
mp,ex,916,39465
mp,nuxy,916,0.28
mp,dens,916,120/(1000*g)
mp,damp,916,0.021/df

/COM - Material 917, Soil
mp,ex,917,38565
mp,nuxy,917,0.28
mp,dens,917,120/(1000*g)
mp,damp,917,0.023/df

/COM - Material 918, Soil
mp,ex,918,37715
mp,nuxy,918,0.28
mp,dens,918,120/(1000*g)
mp,damp,918,0.025/df

/COM - Material 919, Soil
mp,ex,919,41496
mp,nuxy,919,0.28
mp,dens,919,120/(1000*g)
mp,damp,919,0.024/df
```

Far-Soil.txt

```
et,9,solid45          ! Use Elment type SOLID45
for Far Soil
et,10,mass21
r,1001,mass,mass,mass
type,9

asel,u,area,,1,amaxns ! unselect all reas
vsel,u,volu,,1,vmaxns ! unselect all volumes

/COM - Generate Keypoints at full model radius
*do,i,1,tanksoil
k,kmaxns+i,soil_radius,0,soilz(i)
*enddo

/COM - Generate areas outside excavated soil
*do,i,1,tanksoil-1
kp1=kp(soilx(i),0,soilz(i))
kp2=kp(soil_radius,0,soilz(i))
kp3=kp(soil_radius,0,soilz(i+1))
kp4=kp(soilx(i+1),0,soilz(i+1))
a,kp1,kp2,kp3,kp4
*enddo

vrotat,all,,,,,,1,ct_kps,180,2
cm,far-soil-volu,volu
*do,i,1,tanksoil-1
cmsel,s,far-soil-volu
vsel,r,loc,z,soilz(i),soilz(i+1)
vatt,900+i,,9                            ! Assign
attributes
aslv
lsla
lsel,r,loc,x,soilx(i)
lesize,all,,arcsize                      ! Match
excavated soil meshing
lsla
lsel,r,loc,x,soilx(i+1)
lesize,all,,arcsize                      ! Match
excavated soil meshing
lsla
lsel,r,loc,x,soil_radius
lsel,r,loc,z,soilz(i)
lesize,all,,arcsize                      ! Match
excavated soil meshing
lsla
lsel,r,loc,x,soil_radius
lsel,r,loc,z,soilz(i+1)
lesize,all,,arcsize                      ! Match
excavated soil meshing
*enddo

/COM - Mesh soil outside excavated soil
cmsel,s,far-soil-volu
esize,30
vmesh,all
csys,1
esel,s,type,,9
nsle
!nrotat,all                              ! Rotate
all nodes to cylidrical coordinates
cm,far-soil-top,elem

/COM - Connect new soil elements to excavated
soil at interface
*do,i,1,tanksoil
nsel,s,loc,x,soilx(i)
nsel,r,loc,z,soilz(i)
cmsel,u,excav-wall
nummrg,node
*enddo

*get,KMAXtemp,KP,0,num,max
*get,LMAXtemp,LINE,0,num,max
*get,AMAXtemp,AREA,0,num,max
*get,VMAXtemp,VOLU,0,num,max

ksel,u,kp,,all
asel,u,area,,all
vsel,u,volu,,all

/COM - Generate Keypoint below tank for five
layers
*do,i,0,deepsoil-tanksoil-5
k,kmaxtemp+5*i+1,0,0,soilz(i+tanksoil)
               ! Keypoint on centerline
k,kmaxtemp+5*i+2,ctx(ct_kps-1-
i),0,soilz(i+tanksoil) ! Keypoint to flare
central area under tank
k,kmaxtemp+5*i+3,ctx(bm_kp+1),0,soilz(i+tanksoil
)       ! Keypoint under edge of tank
```

```
k,kmaxtemp+5*i+4,soilx(tanksoil),0,soilz(i+tanks
oil)    ! Keypoint under edge of excavated soil
k,kmaxtemp+5*i+5,soil_radius,0,soilz(i+tanksoil)
        ! Keypoint at edge of model
*enddo

/COM - Generate Keypoint below tank to full
depth
*do,i,5,deepsoil-tanksoil
k,kmaxtemp+5*i+1,0,0,soilz(i+tanksoil)
               ! Keypoint on centerline
k,kmaxtemp+5*i+2,ctx(ct_kps-
5),0,soilz(i+tanksoil) ! Keypoint for central
soil area
k,kmaxtemp+5*i+3,ctx(bm_kp+1),0,soilz(i+tanksoil
)       ! Keypoint under edge of tank
k,kmaxtemp+5*i+4,soilx(tanksoil),0,soilz(i+tanks
oil)    ! Keypoint under edge of excavated soil
k,kmaxtemp+5*i+5,soil_radius,0,soilz(i+tanksoil)
        ! Keypoint at edge of model
*enddo

*do,i,0,3              ! Area pattern for 1st 4
layers under tank
a,kmaxtemp+5*i+1,kmaxtemp+5*i+2,kmaxtemp+5*(i+1)
+2,kmaxtemp+5*(i+1)+1
a,kmaxtemp+5*i+2,kmaxtemp+5*i+3,kmaxtemp+5*(i+1)
+3,kmaxtemp+5*(i+1)+2
a,kmaxtemp+5*i+3,kmaxtemp+5*i+4,kmaxtemp+5*(i+1)
+4,kmaxtemp+5*(i+1)+3
a,kmaxtemp+5*i+4,kmaxtemp+5*i+5,kmaxtemp+5*(i+1)
+5,kmaxtemp+5*(i+1)+4
*enddo

! Area pattern for transition layer
a,kmaxtemp+5*4+1,kmaxtemp+5*4+2,kmaxtemp+5*(4+1)
+2,kmaxtemp+5*(4+1)+1
a,kmaxtemp+5*4+2,kmaxtemp+5*4+3,kmaxtemp+5*4+4,k
maxtemp+5*(4+1)+4,kmaxtemp+5*(4+1)+2
a,kmaxtemp+5*4+4,kmaxtemp+5*4+5,kmaxtemp+5*(4+1)
+5,kmaxtemp+5*(4+1)+4

*do,i,5,10             ! Area pattern to bottom
of model
a,kmaxtemp+5*i+1,kmaxtemp+5*i+2,kmaxtemp+5*(i+1)
+2,kmaxtemp+5*(i+1)+1
a,kmaxtemp+5*i+2,kmaxtemp+5*i+4,kmaxtemp+5*(i+1)
+4,kmaxtemp+5*(i+1)+2
a,kmaxtemp+5*i+4,kmaxtemp+5*i+5,kmaxtemp+5*(i+1)
+5,kmaxtemp+5*(i+1)+4
*enddo

/COM - divide line interfacing with bottom of
tank to match tank meshing
lsla
lsel,r,loc,z,soilz(tanksoil)
lsel,r,loc,x,ctx(ct_kps-1),ctx(bm_kp+1)
ratio=(ctx(ct_kps-1)-ctx(ct_kps-2))/(ctx(ct_kps-
1)-ctx(bm_kp+1))
ldiv,all,ratio
*get,LMAXtemp,LINE,0,num,max
*do,i,1,8
lsla
lsel,r,loc,z,soilz(tanksoil)
lsel,r,loc,x,ctx(ct_kps-1-i),ctx(bm_kp+1)
ratio=(ctx(ct_kps-1-i)-ctx(ct_kps-2-
i))/(ctx(ct_kps-1-i)-ctx(bm_kp+1))
ldiv,all,ratio
*enddo
```

```
/COM - Move Keypoints to match tank bottom
vertical locations
lsla
*do,i,0,ct_kps-bm_kp-1
kact=kp(ctx(ct_kps-i),0,soilz(tanksoil))
kmodif,kact,ctx(ct_kps-i),0,ctz(ct_kps-i)
*enddo

ksel,a,kp,,1,ct_kps,ct_kps-1          ! Select
Keypoints for rotation axis
vrotat,all,,,,,,1,ct_kps,180,2                  !
Develop volumes
cm,deep-soil-volu,volu
*do,i,tanksoil,deepsoil-1             ! Assign
attributes
vsel,s,loc,z,soilz(i),soilz(i+1)
vatt,900+i,,9
*enddo

/COM - Control meshing to match model slices
cmsel,s,deep-soil-volu
aslv
lsla
lsel,r,loc,x,soil_radius
lesize,all,,arcsize
lsla
lsel,r,loc,x,soilx(tanksoil)
lesize,all,,arcsize
lsla
lsel,r,loc,x,ctx(bm_kp+1)
lesize,all,,arcsize


vsel,u,loc,x,0,soilx(tanksoil)
vmesh,all                                       !
Mesh outside volumes
vsel,s,loc,x,ctx(ct_kps-5),soilx(tanksoil)
vsel,r,loc,z,soilz(tanksoil+5),soilz(deepsoil)
esize,22
vmesh,all                                       !
Mesh under excavated soil and tank except for
central area

cmsel,s,deep-soil-volu
vsel,r,loc,x,0,ctx(ct_kps-5)                    !
Select volumes under center of tank
aslv
asel,r,loc,z,soilz(tanksoil)                    !
Select soil area at bottom of tank
lsla
lsel,r,loc,x,ctx(ct_kps-1)                      !
Select Lines on outside of center area
lesize,all,,arcsize                             !
Control mesh for slices
lsla
lsel,u,loc,x,ctx(ct_kps-1)
lesize,all,,,midsize                            !
control mesh on inside of area
aslv
lsla
cmsel,s,deep-soil-volu
vsel,r,loc,x,0,ctx(ct_kps-5)
aslv
lsla
lsel,r,loc,z,soilz(tanksoil),soilz(tanksoil+1)
lsel,u,loc,z,soilz(tanksoil)
lsel,u,loc,z,soilz(tanksoil+1)
lesize,all,,,3                                  !
Control meshing under tank
cmsel,s,deep-soil-volu
```

```
vsel,r,loc,x,0,ctx(ct_kps-5)
aslv
lsla
lsel,r,loc,z,soilz(tanksoil+1),soilz(tanksoil+2)
lsel,u,loc,z,soilz(tanksoil+1)
lsel,u,loc,z,soilz(tanksoil+2)
lesize,all,,,2                              !
Control meshing under tank
cmsel,s,deep-soil-volu
vsel,r,loc,x,0,ctx(ct_kps-5)
aslv
asel,r,loc,z,soilz(tanksoil)
type,1
amesh,all                                   !
mesh area at tank/soil interface
vsweep,all                                  !
Sweep mesh to bottom of model
aclear,all                                  !
Clear Pattern

cmsel,s,deep-soil-volu
aslv
lsla
lsel,r,loc,z,soilz(tanksoil+1)
lsel,r,loc,x,ctx(ct_kps-2),ctx(bm_kp+1)
lsel,u,loc,x,ctx(ct_kps-2)
lsel,u,loc,x,ctx(bm_kp+1)
lesize,all,,,8                              !
Control meshing under tank

lsla
lsel,r,loc,z,soilz(tanksoil+2)
lsel,r,loc,x,ctx(ct_kps-3),ctx(bm_kp+1)
lsel,u,loc,x,ctx(ct_kps-3)
lsel,u,loc,x,ctx(bm_kp+1)
lesize,all,,,6                              !
Control meshing under tank

lsla
lsel,r,loc,z,soilz(tanksoil+3)
lsel,r,loc,x,ctx(ct_kps-4),ctx(bm_kp+1)
lsel,u,loc,x,ctx(ct_kps-4)
lsel,u,loc,x,ctx(bm_kp+1)
lesize,all,,,4                              !
Control meshing under tank

lsla
lsel,r,loc,z,soilz(tanksoil+4)
lsel,r,loc,x,ctx(ct_kps-5),ctx(bm_kp+1)
lsel,u,loc,x,ctx(ct_kps-5)
lsel,u,loc,x,ctx(bm_kp+1)
lesize,all,,,2                              !
Control meshing under tank

*do,i,0,2
lsla
lsel,r,loc,z,soilz(tanksoil+i)
lsel,r,loc,x,ctx(bm_kp+1),soilx(tanksoil)
lsel,u,loc,x,ctx(bm_kp+1)
lsel,u,loc,x,soilx(tanksoil)
lesize,all,,,4-i
        ! Control meshing under tank
*enddo

cmsel,s,deep-soil-volu
aslv
lsla
lsel,r,loc,x,ctx(bm_kp+1)
lsel,r,loc,z,soilz(tanksoil),soilz(tanksoil+1)
lsel,u,loc,z,soilz(tanksoil)
lsel,u,loc,z,soilz(tanksoil+1)
ldiv,all,2                                  !
Control meshing under tank

cmsel,s,deep-soil-volu
aslv
lsla
lsel,r,loc,z,soilz(tanksoil)
lsel,r,loc,x,ctx(ct_kps-2),ctx(bm_kp+1)
lesize,all,,arcsize
        ! Control meshing for slices

*do,i,0,4
vsel,s,loc,z,soilz(tanksoil+i),soilz(tanksoil+1+
i)
vsel,r,loc,x,ctx(ct_kps-1-i),soilx(tanksoil)
aslv
asel,r,loc,y,0
type,1
amesh,all                                   !
Mesh area for sweep pattern
vsweep,all                                  !
Mesh volumes
aclear,all                                  !
Clear pattern
*enddo

esel,s,type,,9
nsle
nummrg,node                    ! Merge bottom
soil to rest of model

nsel,s,loc,x,68,320
nummrg,node

esel,s,type,,8,9
nsle
nsel,r,loc,z,soilz(9)
nsel,r,loc,x,41,67
cpint,uz


type,10
real,1001

csys,0
nsel,s,loc,z,soilz(deepsoil)
csys,1
nsel,r,loc,x,320
csys,0
nsel,r,loc,x,0
*get,master_node,node,,num,max
d,master_node,all
allsel

e,master_node                  ! Large mass for
excitation

csys,1
nsel,s,loc,z,soilz(9),soilz(10)
nsel,r,loc,x,0,soilx(9)
esln,,1
esel,r,type,,9
cm,bottom-soil,elem
```

Interface.txt

```
et,21,combin14,,1
et,22,combin14,,2
et,23,combin14,,3
```

```
r,201,1e8
r,202,1e8
r,203,1e8

esel,none
/COM - Create Interface Elements at Bottom of
Concrete Wall
cmsel,s,wall-int
type,21
real,201
eintf

type,22
real,202
eintf

type,23
real,203
eintf

cm,wall-int-spr,elem
esel,none

/COM - Create Interface Elements between primary
tank and insulating concrete
cmsel,s,primary-int
type,21
real,201
eintf

type,22
real,202
eintf

type,23
real,203
eintf

cm,primary-int-spr,elem


esel,none
/COM - Create Interface Elements between
concrete tank and insulating concrete
cmsel,s,insul-int
type,21
real,201
eintf

type,22
real,202
eintf

type,23
real,203
eintf

cm,insul-int-spr,elem
```

Interface2.txt

```
/COM, Create components for wall and dome of
concrete tank and excavated soil for interface
coupling
csys,1
cmsel,s,conc-dome_wall-n
nsel,r,loc,x,ctx(14),ctx(14)+.1
esln,s,1
cmsel,u,liner
cm,conc-wall-e,elem
cm,conc-wall-n,node

cmsel,s,conc-dome_wall-e
cmsel,s,conc-dome_wall-n
cmsel,u,conc-wall-e
nsle,s,1
cm,conc-dome-e,elem
cm,conc-dome-n,node

cmsel,s,excav-soil
nsle,s,1
nsel,r,loc,x,ctx(13)
nsel,r,loc,z,ctz(14),ctz(22)
esln,s
cm,excav-wall-e,elem
cm,excav-wall-n,node

cmsel,s,excav-soil
nsle,s,1
nsel,r,loc,x,0,ctx(14)
nsel,u,loc,z,0,soilz(2)
nsel,u,loc,z,ctz(15),ctz(22)
cm,ntemp,node
nsel,r,loc,z,-11,-13.4
nsel,u,loc,x,0,28
cm,ntemp1,node
cmsel,s,ntemp
cmsel,u,ntemp1
esln
cm,excav-dome-n,node
cm,excav-dome-e,elem

/COM, Create wall soil to concrete tank
interface elements
cmsel,s,conc-wall-n
cmsel,a,excav-wall-n
cm,conc-excav-wall-int,node

cmsel,s,conc-dome-n
cmsel,a,excav-dome-n
cm,conc-excav-dome-int,node

! spring constants
! wall
r,301,1e8
r,302,1e8
r,303,1e8

! dome
r,304,1e8
r,305,1e8
r,306,1e8

! slab
r,307,1e8
r,308,1e8
r,309,1e8

! concrete to soil
! slab
r,307,1e8
r,308,1e8
r,309,1e8

! concrete to excavated soil
r,310,1e8
esel,none
```

```
/COM, Create soil to concrete tank interface
elements
! add wall interface elements
cmsel,s,conc-wall-n
cmsel,a,excav-wall-n
cm,conc-excav-wall-int,node

type,21
real,301
eintf

type,22
real,302
eintf

type,23
real,303
eintf
cm,conc-excav-wall-spr,elem
esel,none

! add dome interface elements
cmsel,s,conc-dome-n
cmsel,a,excav-dome-n
cm,conc-excav-dome-int,node

type,21
real,304
eintf

type,22
real,305
eintf

type,23
real,306
eintf
cm,conc-excav-dome-spr,elem
esel,none

/COM, Create concrete slab to soil interface
elments
esel,s,type,,9
nsle
nsel,r,loc,z,ctz(23)
nsel,r,loc,x,0,ctx(23)
cm,soil-slab,node
allsel

esel,none
cmsel,s,conc-slab
cmsel,a,soil-slab
type,21
real,307
eintf

type,22
real,308
eintf

type,23
real,309
eintf
cm,conc-soil-slab-spr,elem
esel,none
allsel

/COM, Create concrete slab to excavated soil
elements
r,310,1e8
cmsel,s,excav-soil
nsle
nsel,r,loc,z,soilz(9)
nsel,r,loc,x,ctx(14),ctx(23)
cm,excav-footing,node

cmsel,s,conc-slab
nsel,r,loc,x,ctx(14),ctx(23)
cm,conc-footing,node

cmsel,s,excav-footing
cmsel,a,conc-footing

esel,none
type,23
real,310
eintf
cm,conc-soil-footing-spr,elem
allsel
```

Slave.txt

```
/COM - Develop Slave Boundarz Conditions
/COM - 20 Layer Model

csys,1                          ! Set Cylindrical
Coordinates
*get,CPMAX,CP,0,num,max                 ! Counter
for Couple Set Numbers
nsel,s,loc,x,soil_radius        ! Select soil
exterior surface nodes
csys,0                          ! Set Cartesian
Coordinates
nrotat,all                      ! Rotate into
Global Cartesian Coordinates
nsel,s,loc,z,soilz(deepsoil)    ! Select all Base
nodes
nrotat,all                      ! Rotate into
Global Cartesian Coordinates

csys,1                          ! Set Cylindrical
Coordinates
*do,i,1,deepsoil-1,1            ! Cycle through
each soil layer
nsel,s,loc,x,soil_radius        ! Select all
exterior nodes
nsel,r,loc,z,soilz(i)           ! Select nodes by
layer
cp,3*i-2+cpmax,ux,all           ! Couple in X
cp,3*i+cpmax,uz,all             ! Couple in Z
nsel,u,loc,y,0                  ! Unselect nodes
on Symmetry Plane
nsel,u,loc,y,180
cp,3*i-1+cpmax,uy,all           ! Couple in Y
*enddo

nsel,s,loc,z,soilz(deepsoil)    ! Select base
nodes
nsel,u,loc,z,320-.1,320+.1
cp,deepsoil*10+1+cpmax,ux,all ! Couple in X
cp,deepsoil*10+2+cpmax,uy,all ! Couple in Y
cp,deepsoil*10+3+cpmax,uz,all ! Couple in Z

allsel
```

Boundary.txt

```
/COM - Fix symmetry face
```

```
allsel
csys,0
nsel,s,loc,y,0
d,all,uy
csys,1

cmsel,s,conc-tank
cmsel,a,primary-tank
nsle
csys,0
nsel,r,loc,y,0
d,all,rotx
d,all,rotz
csys,1

allsel

!esel,s,type,,24
!nsle
!cmsel,u,conc-slab
!ddele,all,uy
!allsel
```

Outer-Spar.txt

```
! deinfe element type, material and real
constants
et,30,link8            ! rigid link to be place
between couping and boundry conditions

mp,ex,300,10e9         ! high modulus to create
a rigid link
mp,dens,300,0          ! massless rigid link
r,300,1                ! cross-sectional area of
rigid link

! select elements and define rigid links
nsle
nsel,s,loc,x,soil_radius
nsel,u,loc,y,-10,-170
cm,ntemp,node

type,30
mat,300
real,300

*do,i,1,20
cmsel,s,ntemp
nsel,r,loc,z,soilz(i)
eintf,51
*enddo

allsel
```

Live_Load.txt

```
! select nodes to apply concentrated live load
over - 10 ft radius
allsel
nsel,s,loc,z,0
nsel,r,loc,x,0,11
cm,n-live,node
*get,nodes,node,,count        ! count the number
of nodes selected
*get,nstart,node,,num,min     ! get min node
number

live_load-200000     ! live load 100 tons  (lbs)
live_mass-live_load/(2*g*1000*nodes)  ! convert
live load to slugs/node selected

R,1002,live_mass,live_mass,live_mass
type,10
real,1002

cmsel,s,n-live
cm,nlive,node                   ! temporary
counter for nodes

*do,i,1,nodes
cmsel,s,nlive
*get,cnode,node,,num,min
e,cnode
nsel,u,node,,cnode
cm,nlive,node
*enddo

esel,s,real,,1002
cm,live-load,elem
allsel
```

Slosh-TH.txt

```
cmsel,s,conc-tank
nsle
nsel,r,loc,z,ctz(33)
cp,351,ux,all
cp,352,uy,all
cp,353,uz,all
*get,mass_node,node,0,num,min
d,mass_node,uy
d,mass_node,uz
d,mass_node,rotx
d,mass_node,roty
d,mass_node,rotz

r,1003,mass,massm,masss
type,10
real,1003
e,mass_node

allsel
esel,u,type,,8,10
esel,u,type,,30
esel,u,real,,301,303
esel,a,real,,1003
nsle
cm,tank-model,elem
cmsel,s,tank-model
```

Waste-Reaction.txt

```
/post1
*dim,REACTX,,2049
*dim,REACTZ,,2049

cmsel,s,waste
cmsel,a,waste-surf
*do,i,1,2049
set,i
fsum,,cont
*get,REACTX(i),FSUM,0,ITEM,FX
*get,reactz(i),FSUM,0,ITEM,FZ
*enddo
/out,Waste-Reaction,out
```

```
*vwrite
('Total Waste Forces')
*vwrite
('     Fx         FZ')
*vwrite,reactx(1),reactz(1)
(f10.1,f10.1)
/out
```

Waste-Contact.txt (422 In Level)

```
/post26
numvar,200
*do,z,2,199
VARDEL,z
*enddo

*do,i,1,20
*do,j,1,19
esol,(2+j),(5500+i+20*j),,smisc,13,pr%(5500+i+20
*j)%
*enddo

*do,j,20,21
esol,(2+j),(5900-2+j+2*i),,smisc,13,pr%(5900-
2+j+2*i)%
*enddo

LINES,2050
extrem
/OUT,Waste-Cont_%(9*i)%max,OUT
extrem,3,200
/OUT

/OUT,Waste-Cont_%(9*i)%th,OUT
*do,k,1,21
PRVAR,2+k
*enddo
/OUT

*enddo
```

Waste-Contact.txt (452 In Level)

```
/post26
numvar,200
*do,z,2,200
VARDEL,z
*enddo

*do,i,1,20
*do,j,1,2
esol,(2+j),(6300+i+20*j),,smisc,13,pr%(6300+i+20
*j)%
*enddo

*do,j,3,21
esol,(2+j),(5670+i+20*j),,smisc,13,pr%(5670+i+20
*j)%
*enddo

LINES,2050
extrem
/OUT,Waste-Cont_%(9*i)%max,OUT
extrem,3,200
/OUT

/OUT,Waste-Cont_%(9*i)%th,OUT
*do,k,1,21
PRVAR,2+k
*enddo
/OUT

*enddo
```

Waste-Contact.txt (460 In Level)

```
/post26
numvar,200
*do,z,2,200
VARDEL,z
*enddo

*do,i,1,20
*do,j,1,2
esol,(2+j),(6300+i+20*j),,smisc,13,pr%(6300+i+20
*j)%
*enddo

*do,j,3,21
esol,(2+j),(5670+i+20*j),,smisc,13,pr%(5670+i+20
*j)%
*enddo

LINES,2050
extrem
/OUT,Waste-Cont_%(9*i)%max,OUT
extrem,3,200
/OUT

/OUT,Waste-Cont_%(9*i)%th,OUT
*do,k,1,21
PRVAR,2+k
*enddo
/OUT

*enddo
```

Stress-Primary.txt

```
! extract primary tank stress components at the
top, middel and bottom surface of the shell

shell,top
/input,stress-compt,txt

shell,mid
/input,stress-compm,txt

shell,bot
/input,stress-compb,txt
```

Stress-Compb.txt

```
/post26

*do,z,2,199
VARDEL,z
*enddo

*do,i,1,20
*do,j,1,33
esol,(2+j),(741+i+20*j),,s,x,sx%(741+i+20*j)%-b
esol,(35+j),(741+i+20*j),,s,y,sy%(741+i+20*j)%-b
esol,(68+j),(741+i+20*j),,s,z,sz%(741+i+20*j)%-b
esol,(101+j),(741+i+20*j),,s,xy,sxy%(741+i+20*j)
%-b
```

```
esol,(134+j),(741+i+20*j),,s,yz,syz%(741+i+20*j)
%-b
esol,(167+j),(741+i+20*j),,s,xz,sxz%(741+i+20*j)
%-b
*enddo

LINES,2050
extrem
/OUT,Stress-pt_%(9*i)%max-b,OUT
extrem,3,200
/OUT

/OUT,Stress-pt_%(9*i)%th-b,OUT
*do,k,1,33
PRVAR,2+k,35+k,68+k,101+k,134+k,167+k
*enddo
/OUT

*enddo
```

Stress-Compm.txt

```
/post26

*do,z,2,199
VARDEL,z
*enddo

*do,i,1,20
*do,j,1,33
esol,(2+j),(741+i+20*j),,s,x,sx%(741+i+20*j)%-m
esol,(35+j),(741+i+20*j),,s,y,sy%(741+i+20*j)%-m
esol,(68+j),(741+i+20*j),,s,z,sz%(741+i+20*j)%-m
esol,(101+j),(741+i+20*j),,s,xy,sxy%(741+i+20*j)
%-m
esol,(134+j),(741+i+20*j),,s,yz,syz%(741+i+20*j)
%-m
esol,(167+j),(741+i+20*j),,s,xz,sxz%(741+i+20*j)
%-m
*enddo

LINES,2050
extrem
/OUT,Stress-pt_%(9*i)%max-m,OUT
extrem,2,200
/OUT

/OUT,Stress-pt_%(9*i)%th-m,OUT
*do,k,1,33
PRVAR,2+k,35+k,68+k,101+k,134+k,167+k
*enddo
/OUT

*enddo
```

Stress-Compt.txt

```
/post26

*do,z,2,199
VARDEL,z
*enddo

*do,i,1,20
*do,j,1,33
esol,(2+j),(741+i+20*j),,s,x,sx%(741+i+20*j)%-t
esol,(35+j),(741+i+20*j),,s,y,sy%(741+i+20*j)%-t
esol,(68+j),(741+i+20*j),,s,z,sz%(741+i+20*j)%-t
esol,(101+j),(741+i+20*j),,s,xy,sxy%(741+i+20*j)
%-t
esol,(134+j),(741+i+20*j),,s,yz,syz%(741+i+20*j)
%-t
esol,(167+j),(741+i+20*j),,s,xz,sxz%(741+i+20*j)
%-t
*enddo

LINES,2050
extrem
/OUT,Stress-pt_%(9*i)%max-t,OUT
extrem,2,200
/OUT

/OUT,Stress-pt_%(9*i)%th-t,OUT
*do,k,1,33
PRVAR,2+k,35+k,68+k,101+k,134+k,167+k
*enddo
/OUT

*enddo
```

Waste-Surface-AP.txt

```
/post26
numvar,200
*do,z,2,200
VARDEL,z
*enddo

*do,i,0,20
*do,j,2,9
angley--arcsize*(i)
cmsel,s,waste
nsle
nsel,r,loc,y,angley
nsel,r,loc,x,ptx(pt_kps-j)
nsel,r,loc,z,ptz(wastet)
*get,nmax,node,,num,max
nsol,(2+j),(nmax),u,z,uz%(nmax)%
*enddo

cmsel,s,waste
nsle
nsel,r,loc,y,angley
nsel,r,loc,x,ptx(wastet)
nsel,r,loc,z,ptz(wastet)
*get,nmax,node,,num,max
nsol,(3+j),(nmax),u,z,uz%(nmax)%

LINES,2050
extrem
/OUT,Waste-Surf_%(9*i)%max,OUT
extrem,3,200
/OUT

/OUT,Waste-Surf_%(9*i)%th,OUT
*do,k,2,10
PRVAR,2+k
*enddo
/OUT

*enddo
```

Waste-Surface-AY.txt

```
/post26
numvar,200
*do,z,2,200
```

```
VARDEL,z
*enddo

*do,i,0,20
*do,j,2,8
angley=-arcsize*(i)
cmsel,s,waste
nsle
nsel,r,loc,y,angley
nsel,r,loc,x,ptx(pt_kps-j)
nsel,r,loc,z,ptz(wastet)
*get,nmax,node,,num,max
nsol,(2+j),(nmax),u,z,uz%(nmax)%
*enddo

cmsel,s,waste
nsle
nsel,r,loc,y,angley
nsel,r,loc,x,ptx(wastet)
nsel,r,loc,z,ptz(wastet)
*get,nmax,node,,num,max
nsol,(3+j),(nmax),u,z,uz%(nmax)%

LINES,2050
extrem
/OUT,Waste-Surf_%(9*i)%max,OUT
extrem,3,200
/OUT

/OUT,Waste-Surf_%(9*i)%th,OUT
*do,k,2,11
PRVAR,2+k
*enddo
/OUT

*enddo
```

Flex-AP-Free Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/prep7

g=32.2                        ! Gravity (ft/sec)

DF=40                         ! Factor for beta
(stiffness) damping
ALPHA=0.4                     ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt       ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt         ! Develop concrete
tank
/input,primary-props-AY-uniform,txt  ! Run file
defining AP Primary tank properties
/input,primary,txt            ! Develop Primary
tank
/input,insulate,txt           ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AP,txt            ! Develop
waste model
/input,bolts-ns,txt           ! Develop J-Bolt
model
/input,near-soil-1,txt        ! Develop
excavated soil model
/input,far-soil,txt           ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt              ! Develop slaved
boundary conditions
/input,boundary,txt           ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt          ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt

/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-primary,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z=148414.59
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM=1000                         !NUMBER OF TIME
STEPS
DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_x,,2048

*VREAD,A_1_x(1),Dome-Accel-X,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0.05*g,0,g
SOLVE
SAVE

!ddele,mass_node,ux

acel,0,0,g
TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
!f,mass_node,fx,a_1_x(itim)*g*mass
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Flex-AP-Free Vertical Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/prep7

g=32.2                        ! Gravity (ft/sec)

DF=40                         ! Factor for beta
(stiffness) damping
ALPHA=0.4                     ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt       ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt         ! Develop concrete
tank
/input,primary-props-AY-uniform,txt   ! Run file
defining AP Primary tank properties
/input,primary,txt            ! Develop Primary
tank
/input,insulate,txt           ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AP,txt            ! Develop
waste model
/input,bolts-ns,txt           ! Develop J-Bolt
model
/input,near-soil-1,txt        ! Develop
excavated soil model
/input,far-soil,txt           ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt              ! Develop slaved
boundary conditions
/input,boundary,txt           ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt          ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt


/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-primary,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z=148414.59
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM=1000                         !NUMBER OF TIME
STEPS
DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_x,,2048


/Title,file:Fluid/Structure Interaction, Uniform
Flexible Tank 452 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0,0,g*0.95
SOLVE
SAVE

!ddele,mass_node,ux

acel,0,0,g
TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
!f,mass_node,fx,a_1_x(itim)*g*mass
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Flex-AP-TH Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/prep7

g=32.2                       ! Gravity (ft/sec)

DF=40                        ! Factor for beta
(stiffness) damping
ALPHA=0.4                    ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt        ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt         ! Develop concrete
tank
/input,primary-props-AY-uniform,txt   ! Run file
defining AP Primary tank properties
/input,primary,txt            ! Develop Primary
tank
/input,insulate,txt           ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AP,txt             ! Develop
waste model
/input,bolts-ns,txt           ! Develop J-Bolt
model
/input,near-soil-1,txt        ! Develop
excavated soil model
/input,far-soil,txt           ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt              ! Develop slaved
boundary conditions
/input,boundary,txt           ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt          ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt

/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-primary,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z=148414.59
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM=2048                              !NUMBER OF TIME
STEPS
DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_x,,2048

*VREAD,A_1_x(1),Dome-Accel-X,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0,0,g
SOLVE
SAVE

ddele,mass_node,ux

TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
f,mass_node,fx,a_1_x(itim)*g*mass
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Flex-AP-TH-460 Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/congig,nproc,2
/config,fsplit,1024
/prep7

g=32.2                        ! Gravity (ft/sec)

DF=40                         ! Factor for beta
(stiffness) damping
ALPHA=0.4                     ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt        ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt         ! Develop concrete
tank
/input,primary-props-AY-uniform,txt   ! Run file
defining AP Primary tank properties
/input,primary,txt            ! Develop Primary
tank
/input,insulate,txt           ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AP,txt             ! Develop
waste model
/input,bolts-ns,txt           ! Develop J-Bolt
model
/input,near-soil-1,txt        ! Develop
excavated soil model
/input,far-soil,txt           ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt              ! Develop slaved
boundary conditions
/input,boundary,txt           ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt          ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt

/input,solve-slosh,txt
/input,waste-reaction,txt
/input,contact-waste-AP,txt
/input,stress-primary,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z=148414.59
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto


NTIM=2048                     !NUMBER OF TIME
STEPS


DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_x,,2048

*VREAD,A_1_x(1),Dome-Accel-X,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf

alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0,0,g
SOLVE
SAVE

ddele,mass_node,ux

TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
f,mass_node,fx,a_1_x(itim)*g*mass
SOLVE
SAVE
*ENDDO
FINISH
```

```
/out
```

Flex-AP-TH-V Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/prep7

g-32.2                          ! Gravity (ft/sec)

DF-40                           ! Factor for beta
(stiffness) damping
ALPHA-0.4                       ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt        ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt           ! Develop concrete
tank
/input,primary-props-AY-uniform,txt   ! Run file
defining AP Primary tank properties
/input,primary,txt              ! Develop Primary
tank
/input,insulate,txt             ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AP,txt               ! Develop
waste model
/input,bolts-ns,txt             ! Develop J-Bolt
model
/input,near-soil-1,txt          ! Develop
excavated soil model
/input,far-soil,txt             ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt                ! Develop slaved
boundary conditions
/input,boundary,txt             ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt            ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt



/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-primary,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
massm_z-478.6025
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM-2048                                 !NUMBER OF TIME
STEPS
DT-0.01
TIM-1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_z,,2048

*VREAD,A_1_z(1),Haunch-Accel-Z,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0,0,g
SOLVE
SAVE

ddele,mass_node,uz
save
TIMINT,on
ITIM-1
DS-TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM-DT*ITIM
TIME,TIM+100
f,mass_node,fz,(a_1_z(itim)+1)*g*(mass+massm_z)
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Flex-AY-Free Files

Run-Tank.txt

```
/batch
fini
/clear
/config,nres,3000
/prep7

g=32.2                          ! Gravity (ft/sec)

DF=40                           ! Factor for beta
(stiffness) damping
ALPHA=0.4                       ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt        ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt           ! Develop concrete
tank
/input,primary-props-AY-uniform,txt   ! Run file
defining AP Primary tank properties
/input,primary,txt              ! Develop Primary
tank
/input,insulate,txt             ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AY,txt             ! Develop
waste model
/input,bolts-ns,txt             ! Develop J-Bolt
model
/input,near-soil-1,txt          ! Develop
excavated soil model
/input,far-soil,txt             ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt                ! Develop slaved
boundary conditions
/input,boundary,txt             ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt            ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh,txt
/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-compt,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z=148414.59

/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM=1000                             !NUMBER OF TIME
STEPS
DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/Title,file:Uniform Flexible Tank/Fluid
Interaction, 424 inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0.05*g,0,g
!acel,0,0,g
SOLVE
SAVE
TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
acel,0,0,g
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Flex-AY-Free-V Files

Run-Tank.txt

```
!/batch
fini
/clear
/config,nres,3000
/prep7

g=32.2                         ! Gravity (ft/sec)

DF=40                          ! Factor for beta
(stiffness) damping
ALPHA=0.4                      ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt        ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt          ! Develop concrete
tank
/input,primary-props-AY-uniform,txt   ! Run file
defining AP Primary tank properties
/input,primary,txt             ! Develop Primary
tank
/input,insulate,txt            ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AY,txt             ! Develop
waste model
/input,bolts-ns,txt            ! Develop J-Bolt
model
/input,near-soil-1,txt         ! Develop
excavated soil model
/input,far-soil,txt            ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt               ! Develop slaved
boundary conditions
/input,boundary,txt            ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt           ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh,txt
/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-compt,txt
!/input,all-forces,txt
/out
!/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z=148414.59

/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM=200                              !NUMBER OF TIME
STEPS
DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/Title,file:Uniform Flexible Tank/Fluid
Interaction, 424 inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0.0,0,g*1.1
!acel,0,0,g
SOLVE
SAVE
TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
acel,0,0,g
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Flex-AY-TH Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/prep7

g=32.2                        ! Gravity (ft/sec)

DF=40                         ! Factor for beta
(stiffness) damping
ALPHA=0.4                     ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt       ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt         ! Develop concrete
tank
/input,primary-props-AY-uniform,txt  ! Run file
defining AP Primary tank properties
/input,primary,txt            ! Develop Primary
tank
/input,insulate,txt           ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AY,txt            ! Develop
waste model
/input,bolts-ns,txt           ! Develop J-Bolt
model
/input,near-soil-1,txt        ! Develop
excavated soil model
/input,far-soil,txt           ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt              ! Develop slaved
boundary conditions
/input,boundary,txt           ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt          ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt



/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-primary,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z=148414.59
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM=2048                              !NUMBER OF TIME
STEPS
DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_x,,2048

*VREAD,A_1_x(1),Dome-Accel-X,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0,0,g
SOLVE
SAVE

ddele,mass_node,ux

TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
f,mass_node,fx,a_1_x(itim)*g*mass
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Flex-AY-TH-V Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/prep7

g-32.2                        ! Gravity (ft/sec)

DF-40                         ! Factor for beta
(stiffness) damping
ALPHA-0.4                     ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt       ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt         ! Develop concrete
tank
/input,primary-props-AY-uniform,txt   ! Run file
defining AP Primary tank properties
/input,primary,txt            ! Develop Primary
tank
/input,insulate,txt           ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AY,txt            ! Develop
waste model
/input,bolts-ns,txt           ! Develop J-Bolt
model
/input,near-soil-1,txt        ! Develop
excavated soil model
/input,far-soil,txt           ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt              ! Develop slaved
boundary conditions
/input,boundary,txt           ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt          ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt



/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-primary,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
massm_z-478.6025
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM-2048                    !NUMBER OF TIME
STEPS
DT-0.01
TIM-1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_z,,2048

*VREAD,A_1_z(1),Haunch-Accel-Z,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0,0,g
SOLVE
SAVE

ddele,mass_node,uz
save
TIMINT,on
ITIM-1
DS-TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM-DT*ITIM
TIME,TIM+100
f,mass_node,fz,(a_1_z(itim)+1)*g*(mass+massm_z)
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Rigid-AP-Free Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/prep7

g-32.2                          ! Gravity (ft/sec)

DF-40                           ! Factor for beta
(stiffness) damping
ALPHA-0.4                       ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt        ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt    ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt           ! Develop concrete
tank
/input,primary-props-AY-rigid,txt     ! Run file
defining AP Primary tank properties
/input,primary,txt              ! Develop Primary
tank
/input,insulate,txt             ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AP,txt               ! Develop
waste model
/input,bolts-ns,txt             ! Develop J-Bolt
model
/input,near-soil-1,txt          ! Develop
excavated soil model
/input,far-soil,txt             ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt                ! Develop slaved
boundary conditions
/input,boundary,txt             ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt            ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt



/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-compt,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z-148414.59
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM-500                              !NUMBER OF TIME
STEPS
DT-0.04
TIM-1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_x,,2048

*VREAD,A_1_x(1),Dome-Accel-X,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0.05*g,0,g
SOLVE
SAVE

!ddele,mass_node,ux
acel,0,0,g
TIMINT,on
ITIM-1
DS-TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM-DT*ITIM
TIME,TIM+100
!f,mass_node,fx,a_1_x(itim)*g*mass
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Rigid-AP-TH Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/prep7

g=32.2                          ! Gravity (ft/sec)

DF=40                           ! Factor for beta
(stiffness) damping
ALPHA=0.4                       ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt        ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt           ! Develop concrete
tank
/input,primary-props-AY-rigid,txt     ! Run file
defining AP Primary tank properties
/input,primary,txt              ! Develop Primary
tank
/input,insulate,txt             ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AP,txt             ! Develop
waste model
/input,bolts-ns,txt             ! Develop J-Bolt
model
/input,near-soil-1,txt          ! Develop
excavated soil model
/input,far-soil,txt             ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt                ! Develop slaved
boundary conditions
/input,boundary,txt             ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt            ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt



/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-compt,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z=148414.59
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM=2048                                     !NUMBER OF TIME
STEPS
DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_x,,2048

*VREAD,A_1_x(1),Dome-Accel-X,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0,0,g
SOLVE
SAVE

ddele,mass_node,ux

TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
f,mass_node,fx,a_1_x(itim)*g*mass
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Rigid-AP-TH-460 Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/config,nproc,2
/config,fsplit,1024
/prep7

g=32.2                         ! Gravity (ft/sec)

DF=40                          ! Factor for beta
(stiffness) damping
ALPHA=0.4                      ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt        ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt    ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt          ! Develop concrete
tank
/input,primary-props-AY-rigid,txt     ! Run file
defining AP Primary tank properties
/input,primary,txt             ! Develop Primary
tank
/input,insulate,txt            ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AP,txt             ! Develop
waste model
/input,bolts-ns,txt            ! Develop J-Bolt
model
/input,near-soil-1,txt         ! Develop
excavated soil model
/input,far-soil,txt            ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt               ! Develop slaved
boundary conditions
/input,boundary,txt            ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt           ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt

/input,solve-slosh,txt
/input,waste-reaction,txt
/input,contact-waste-AP,txt
/input,stress-compt,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z=148414.59
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto


NTIM=2048

                                               !NUMBER OF TIME STEPS
DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_x,,2048

*VREAD,A_1_x(1),Dome-Accel-X,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,STRS,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf

alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0,0,g
SOLVE
SAVE

ddele,mass_node,ux

TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
f,mass_node,fx,a_1_x(itim)*g*mass
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Rigid-AP-TH-V Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/prep7

g=32.2                          ! Gravity (ft/sec)

DF=40                           ! Factor for beta
(stiffness) damping
ALPHA=0.4                       ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt          ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt    ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt           ! Develop concrete
tank
/input,primary-props-AY-rigid,txt      ! Run file
defining AP Primary tank properties
/input,primary,txt              ! Develop Primary
tank
/input,insulate,txt             ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AP,txt               ! Develop
waste model
/input,bolts-ns,txt             ! Develop J-Bolt
model
/input,near-soil-1,txt          ! Develop
excavated soil model
/input,far-soil,txt             ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt                ! Develop slaved
boundary conditions
/input,boundary,txt             ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt            ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt



/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-compt,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
massm_z=478.6025
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM=2048                                     !NUMBER OF TIME
STEPS
DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_z,,2048

*VREAD,A_1_z(1),Haunch-Accel-Z,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0,0,g
SOLVE
SAVE

ddele,mass_node,uz

TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
f,mass_node,fz,(a_1_z(itim)+1)*g*(mass+massm_z)
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Rigid-AY-Free Files

Run-Tank.txt

```
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!
/batch
fini
/clear
/config,nres,3000
/prep7

g=32.2                         ! Gravity (ft/sec)

DF=40                          ! Factor for beta
(stiffness) damping
ALPHA=0.4                      ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt        ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt    ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt          ! Develop concrete
tank
/input,primary-props-AY-rigid,txt     ! Run file
defining AP Primary tank properties
/input,primary,txt             ! Develop Primary
tank
/input,insulate,txt            ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AY,txt             ! Develop
waste model
/input,bolts-ns,txt            ! Develop J-Bolt
model
/input,near-soil-1,txt         ! Develop
excavated soil model
/input,far-soil,txt            ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt               ! Develop slaved
boundary conditions
/input,boundary,txt            ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt           ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh,txt
/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-compt,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z=148414.59
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM=500                              !NUMBER OF TIME
STEPS
DT=0.04
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0.05*g,0,g
!acel,0,0,g
SOLVE
SAVE
TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
acel,0,0,g
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Rigid-AY-TH Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/prep7

g=32.2                        ! Gravity (ft/sec)

DF=40                         ! Factor for beta
(stiffness) damping
ALPHA=0.4                     ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt        ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt         ! Develop concrete
tank
/input,primary-props-AY-rigid,txt     ! Run file
defining AP Primary tank properties
/input,primary,txt            ! Develop Primary
tank
/input,insulate,txt           ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AY,txt             ! Develop
waste model
/input,bolts-ns,txt           ! Develop J-Bolt
model
/input,near-soil-1,txt        ! Develop
excavated soil model
/input,far-soil,txt           ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt              ! Develop slaved
boundary conditions
/input,boundary,txt           ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt          ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt



/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-compt,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
!massm_z=148414.59
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM=2048                               !NUMBER OF TIME
STEPS
DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_x,,2048

*VREAD,A_1_x(1),Dome-Accel-X,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0,0,g
SOLVE
SAVE

ddele,mass_node,ux

TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
f,mass_node,fx,a_1_x(itim)*g*mass
SOLVE
SAVE
*ENDDO
FINISH
/out
```

Rigid-AY-TH-V Files

Run-Tank.txt

```
/batch
! PNNL DST Seismic Analysis, Horizontal and
Vertical Seismic Inputs, Best Estimate Soil,
Best Estimate Concrete Properties, AP Primary
Tank Geometry
!

fini
/clear
/config,nres,3000
/prep7

g=32.2                        ! Gravity (ft/sec)

DF=40                         ! Factor for beta
(stiffness) damping
ALPHA=0.4                     ! Alpha damping

/out,tank-out,out
/sys,"X:\07.00 - Quality Assurance\ANSYS
QA\usrcfg.bat" > QA.out
/out,QA,out,,append
/input,tank-coordinates-AP,txt        ! Run file
defining tank coordinates (concrete and primary)
/input,tank-props-rigid,txt   ! Run file
defining fully cracked concrete properties (PNNL
Concrete Properties)
/input,tank-mesh1,txt         ! Develop concrete
tank
/input,primary-props-AY-rigid,txt     ! Run file
defining AP Primary tank properties
/input,primary,txt            ! Develop Primary
tank
/input,insulate,txt           ! Develop
insulating concrete model
/input,liner,txt
/input,waste-solid-AY,txt             ! Develop
waste model
/input,bolts-ns,txt           ! Develop J-Bolt
model
/input,near-soil-1,txt        ! Develop
excavated soil model
/input,far-soil,txt           ! Develop Far-
Field soil model
/input,interface,txt
/input,interface2,txt
/input,slave,txt              ! Develop slaved
boundary conditions
/input,boundary,txt           ! Place base and
symmetry boundary conditions
/input,outer-spar,txt
/input,live_load,txt          ! Apply live load
over a 10ft radius over dome center
/out
/input,slosh-TH,txt



/input,solve-slosh,txt
/input,waste-reaction,txt
/input,waste-contact,txt
/input,stress-compt,txt
!/input,all-forces,txt
/out
/exit
```

Solve-Slosh.txt

```
/prep7
massm_z=478.6025
d,mass_node,all
/out,Slosh,out
/solu
!nlgeom,on
antype,trans
TRNOPT,FULL
lumpm,OFF
!nlgeom,on
NROPT,auto
NTIM=2048                           !NUMBER OF TIME
STEPS
DT=0.01
TIM=1e-06
autots,on
KBC,on
TIMINT,ON,STRU
solcontrol,ON,off,,
ncnv,0,200
LNSRCH,OFF
PRED,on,,on

/COM - Time File

/COM - Dimension Horizontal Input
*DIM,A_1_z,,2048

*VREAD,A_1_z(1),Haunch-Accel-Z,txt
(F7.5)

/Title,file:Fluid/Structure Interaction, Uniform
Rigid Tank 424 Inches
OUTPR,all,NONE,
OUTRES, ALL,NONE,
OUTRES,RSOL,last
OUTRES,NSOL,last
!OUTRES,ESOL,last,conc-tank
OUTRES,ESOL,last,Primary-tank
!OUTRES,ESOL,last,J_bolts
!OUTRES,ESOL,last,liner
outres,esol,last,waste-surf


alphad,alpha
NSUBST,20,200,5,ON
TIME,100
TIMINT,off
acel,0,0,g
SOLVE
SAVE

ddele,mass_node,uz

TIMINT,on
ITIM=1
DS=TIM
NSUBST,2,20,2,ON
*DO,ITIM,1,NTIM,1
TIM=DT*ITIM
TIME,TIM+100
f,mass_node,fz,(a_1_z(itim)+1)*g*(mass+massm_z)
SOLVE
SAVE
*ENDDO
FINISH
/out
```