ANALYSIS OF WASTE STORAGE TANKS SUBJECTED TO SEISMIC LOADING

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ABSTRACT

At the Savannah River Site, High Activity Wastes are stored in carbon steel tanks that are within reinforced concrete vaults. These soil-embedded tank/vault structures are approximately 24m in diameter and 12m deep.

Twenty-seven of these tanks required seismic analysis. The problem was reduced to a limited number of cases of soil-structure interaction and fluid-structure interaction problems.

It was theorized that substantially reduced seismic input could be realized from soil structure interaction (SSI) but that it was also possible that tank-to-tank proximity could result in (re)amplification of the input. To determine the governing seismic input motion, the three dimensional SSI code, SASSI, was used.

Also of concern was fluid response and tank behavior as a function of tank contents viscosity. Tank seismic analyses and studies have been based on low viscosity fluids (water) and the behavior is quite well understood. Typical wastes (salts, sludge), which are highly viscous, have not been the subject of studies to understand the effect of viscosity on seismic response.

Conclusions based on this study provide insight into the quantification of the of seismic inputs for soil structure interaction for a "soft" soil site and provides some conclusions for dealing with the viscosity variable.

INTRODUCTION

Two chemical separation facilities are in use at the Savannah River Site (SRS) to separate and purify the products of SRS reactor operations. The radioactive effluent from these separation facilities is contained in buried tanks, under a controlled environment, for future reprocessing and subsequent disposal by vitrification or concrete entombment. There are 51 such tanks at SRS of which the 24 older ones are planned to be emptied and decommissioned. The remaining 27 will be an integral part of the long range waste management program at SRS. A detailed evaluation of these 27 tanks was required to establish confidence in the capacity to withstand natural phenomena hazards such as earthquakes. There are issues significant to these waste tanks that are not common in commercial tank seismic design and analysis. This paper discusses some of these issues and the methods utilized in the structural analysis of these waste storage tanks.

WASTE TANK DESIGN

The tanks considered in this report are of a double wall design. The external shell of the tank is a cylindrical vault of concrete with a full-height steel liner that terminates at the joint of the roof and the cylinder wall. Inside this vault is a steel tank that holds the waste. The waste is in various states from inviscid liquid to highly viscous or nearly granular at densities up to 2.2 specific gravity. The tank diameter is somewhat smaller than the vault, thus creating an annular space between the tank and the vault. In order for waste to reach outside the confinement boundary three layers of material need to be penetrated. The concrete vault has an outer radius of 14.5m and a height of approximately 12.8m. The wall of the vault is 0.76m thick. The base and the roof are nominally 1.5m thick. The roof of the vault is supported by a 1.8m diameter concrete column, encased by a steel liner, that penetrates the center of the tank and vault liner. The top of the tank is connected to the concrete roof by a tight pattern of Nelson studs which are welded to the steel tank. The tank base is supported by the vault in bearing only. The cross-sectional view of a typical tank is shown in Fig. 1. The entire tank-vault system is embedded in soil.

Tanks such as the one described above exist in varying geometrical configurations in two tank farm areas. The configuration variations result from the physical layout (i.e., arrangement in closely spaced clusters vs. isolated tanks) and from the varying levels of fluid in each tank. The various approximate fill heights in the tanks range from completely full to less than a quarter full, with the contents varying in consistency from supernatant fluid to sludge. In addition, even though in both areas the tanks appear to be buried, the construction sequence of the tanks was significantly different. In one area the tanks were built in excavated pits, each tank was constructed and the tank was then back-filled (tank top at grade). In another area, the tanks were constructed on-grade, and back-fill was placed around each tank resulting in a soil covered structure (tank base at grade).

SIGNIFICANT ISSUES

Significant among the issues relative to waste tanks was the determination of fluid response and tank behavior as a function of the tank content's viscosity. Historically, tank seismic analyses and studies have been based on low viscosity fluids (water), and their behavior is quite well understood (4,5). Typical wastes (salt-sludge), are highly viscous and have not been studied to fully understand the effect of viscosity on seismic response.

Other issues of concern arose from the structure being fully embedded in soil. These included:

1. the magnitude of dynamic lateral earth pressure on the concrete vault,
2. spectral amplification or reduction not predicted by the free field input spectrum due to soil structure interaction,

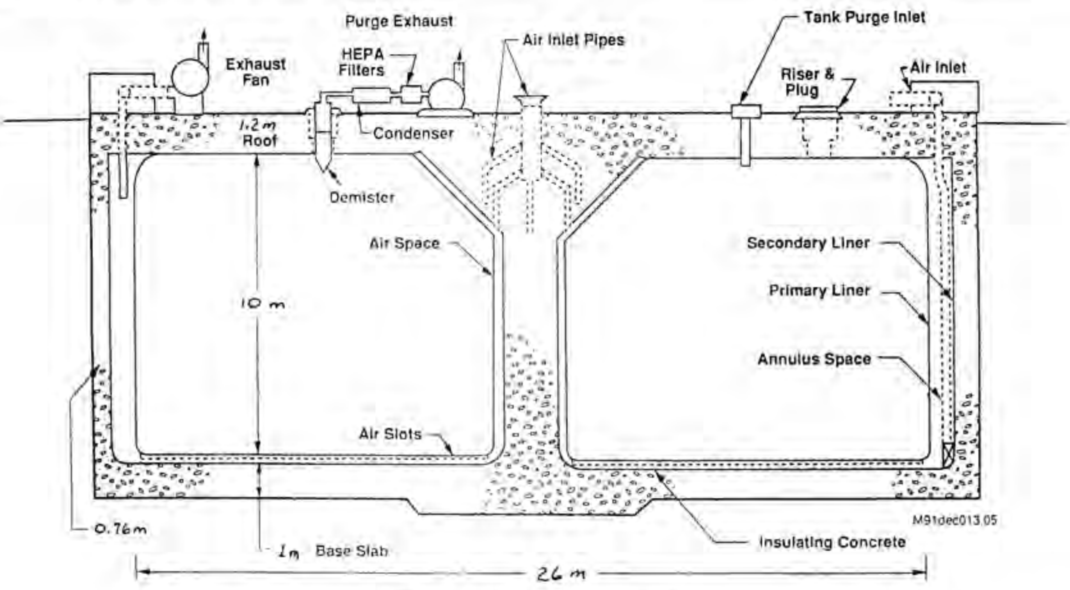

Fig. 1. Waste storage tank.

3. possible amplification of the free field input spectrum from to tank-to-tank interaction due to the close proximity of the tanks to each other,
4. variation on results due to the expected range of soil dynamic properties.

METHODOLOGY

It was not practical to evaluate all the permutations of fill levels, construction methods and adjacent tank proximity for the 27 separate tank cases. This necessitated that all possible tank configurations be studied to determine the essential or governing variables to reduce the problem to the least number of governing cases to optimize analysis effort without introducing excessive conservatism. The ensuing study reduced the problem size to the analysis of three governing cases to bound the effects of soil structure interaction (SSI) and resulted in the separate solutions for SSI and fluid structure interaction (FSI) effects. The SSI cases considered in the analysis are shown in Fig. 2.

Since the problem required the solution to both the SSI and FSI conditions, a suitable computer code was sought. The computer code DYNA3D (1) was found to possess all the necessary material models required for such a combined analysis. This code has soil models and a fluid element model that could accommodate variable viscosity.

The soil model in DYNA3D uses the 'cap' model. To determine the specific properties required for the 'cap' model extensive additional soils testing would be required. This was not possible. To use DYNA3D to determine the dynamic behavior of highly viscous fluids, it was determined that the code should be benchmarked using known solutions (8) for inviscid fluids. This was to be performed by comparing the DYNA3D results with those of closed form solutions for a tank with water subjected to base excitation; first for a tank with rigid walls and second for a tank with flexible walls. The results of the benchmarking indicated a significant difference in results that to date have not been explained or resolved (9).

Since the available soils data was incompatible with DYNA, the fluid behavior was not validated and no other code with the SSI or FSI capabilities was found, the problem was decoupled to address the two issues separately. It was decided that the 3-D soil structure interaction computer code SASSI (2) would be used for the SSI analysis. The tank was analyzed for FSI effects using closed form (hand) solutions.

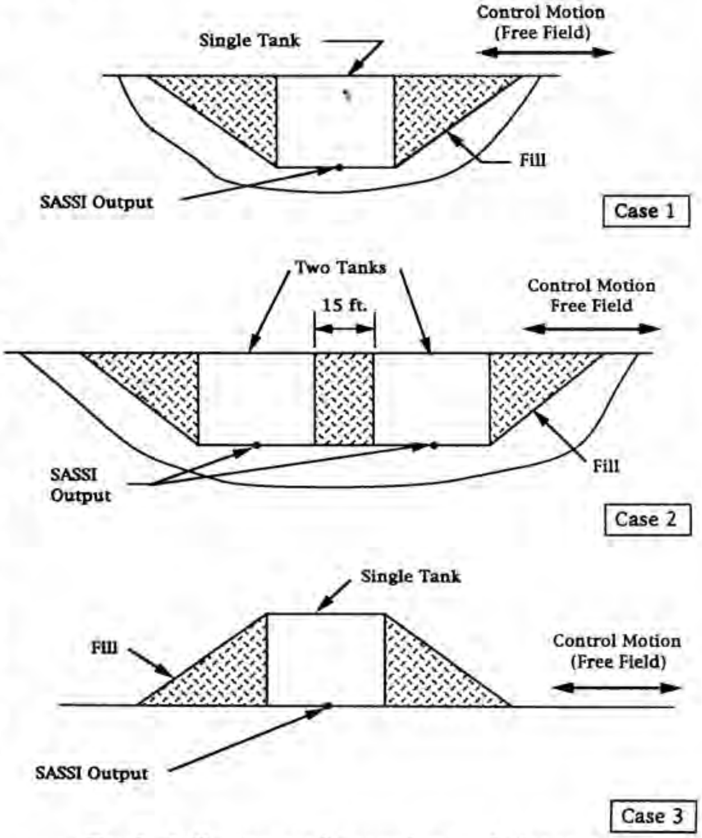

Fig. 2. Soil structure interaction analysis cases.

SSI ANALYSIS

The SASSI model of the concrete vault was developed to account for the mass of the tank and its contents. Hydrodynamic effects of the tank contents on the vaults was considered in this phase of the analysis by modeling the contents as masses attached with horizontal and vertical springs to the vault. The stiffness of the springs were based on the frequency of the tank and contents determined from the FSI analysis. The soil properties used in this analysis were extracted from the soils dynamic tests reports performed for earlier analyses of the tanks. For the current analysis, the best estimates of the soil properties were taken as the weighted average of the soils exploration program data. The upper and lower bound estimates are taken as 2.0 times and 0.67 times the best estimate values respectively.

As a first stage for the SSI analysis, iterations on the soil properties were conducted using the program SHAKE (3). This analysis addresses nonlinear effects in the soil, and yields a horizontally layered site profile with properties that are compatible with the levels of strain in the free field and within each layer. The three cases considered for the SSI analysis were: 1) a single tank with top at grade, 2) two tanks in close proximity with tops at grade, 3) a single tank base at grade. The objective of Case 2 was to determine the inter-tank effect, if any, on the amplified response. In the same study, the response at the tank tops and bases for all cases was compared to the response at the free field to determine the governing motion at the base for input to the FSI model. The vault was modeled using shell elements so the moments and shears arising from the dynamic soil pressure would be taken directly from the SASSI output. In all cases the free field input was a time history corresponding to USNRC Regulatory Guide 1.60. The results of this analysis are shown in Figs. 3a and 3b.

The results indicate that, for cases 1 and 2, there is some reduction of the overall amplified response and in the frequency of interest (approx. 7 hz) for FSI there is a significant reduction in spectral acceleration. Quite surprisingly, for case 3, there is a substantial increase in low frequency spectral acceleration, presumably due to the first soil column frequency, but, as in cases 1 and 2, at FSI frequencies of interest the response is attenuated. For all three cases, the maximum bending moment due to dynamic lateral earth pressure is quite small and essentially negligible when compared to moments due to static earth pressure.

HYDRODYNAMIC ANALYSIS

The intent of the hydrodynamic analysis was to study the tank-contents dynamic behavior during a seismic event. This analysis had to address the effects of three contents variables; tank fill height, density and viscosity. From the analysis, two governing cases evolved. The first case was performed for a tank with contents having a specific gravity of 1.8. This value of specific gravity is the maximum value for which the contents exhibit (inviscid) fluid behavior. The second analysis case was performed for contents with a specific gravity of 2.2. This is the maximum attainable specific gravity value known for the tank contents. For each of the two cases, the hydrodynamic forces and pressures were combined with the hydrostatic loading to obtain liner stresses and reaction forces between the steel liner and the concrete vault. The fill height variable was fixed at the full level since some tanks are filled to the top and this produces the maximum pressure. Additionally, because the tank roofs are supported by the concrete vault, the effect of slosh on the roof was inconsequential.

The first analysis case evaluates the tank-contents dynamic behavior using the flexible tank fluid-structure interaction procedure developed by Veletsos and others (6, 7, 8). For this analysis, the seismic excitation of the impulsive mass (part of the fluid mass that behaves as if rigidly attached to the tank) and the vertical seismic pressure distribution (similar to hydrostatic calculation) used pseudo-acceleration values based on 3% damped design spectra. The convective mass (part of the fluid that vibrates independent of the tank) was based on 0.5% damped design spectra pseudo-acceleration values.

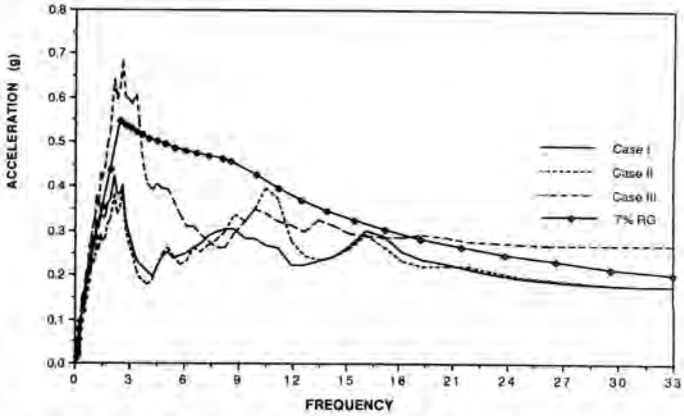

Fig. 3. (a) Base mat response spectra for cases 1,2, & 3 (using best estimate soils data).

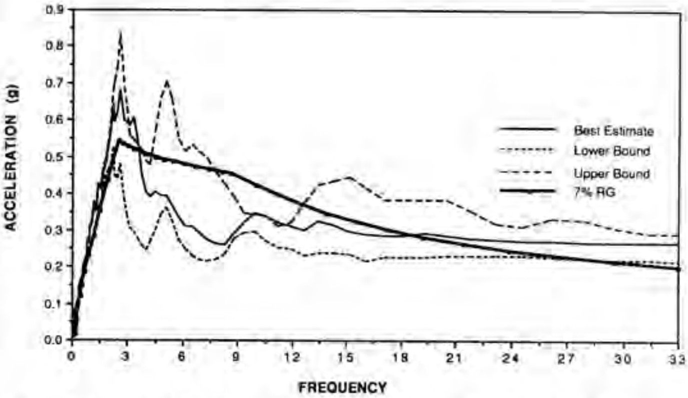

Fig. 3. (b) CASE 3 response spectra at base mat for best estimate soils (BE) data, 0.67×BE and 2.0×BE.

The second analysis case evaluates the dynamic behavior of the tank at 2.2 specific gravity and the total contents lumped onto the structure to conservatively account for highly viscous nature of the contents; ie, all of contents acting in the impulsive mode. The analysis procedure performed closely parallels that used above with a few minor differences/exclusions. Since the contents no longer exhibit fluid behavior, resonant frequencies for the tank with lumped contents only are calculated. The equations for these frequency calculations differ from those used above to obtain fluid-structure frequencies, generally, resulting in a higher fundamental mode. Also, there is no convective response for the non-fluid contents, which results in entirely impulsive hydrodynamic effects. The final difference between the two procedures is the use of 5% damped design spectra pseudo-acceleration values for the horizontal impulsive and vertical seismic excitations. This higher damping is considered an upper bound value for cases where the tank contents have high viscosity. Higher damping may be justified for more granular contents.

For comparison purposes, the pressure distribution was obtained for combined hydrodynamic and hydrostatic pressures for the two tank contents; 1) full of 1.8 specific gravity inviscid fluid and 2) full of 2.2 specific gravity high viscosity material. These analyses used pseudo-acceleration values obtained from spectra generated by the case 3 soil-structure-interaction analysis of the vault-liner-fluid system. While fluid case 1 has only 48% of the mass participating and fluid case 2, by definition, has 100% mass participation, it was found that there is essentially no differences in the pressure distribution. Peak pressure for fluid case 1 was 3.17E5 pascal vs. 3.65E5 pascal for fluid case 2 (46 psi vs. 53 psi). The similarity of the results is further enforced by maximum stress (primary membrane + bending) at the base of the tank for the two cases (tanks anchored top and bottom):

max. stress @ 1.8 sp. gr. = 2.213 E+08 pascal (32.1 ksi)

max. stress @ 2.2 sp. gr. = 2.461 E+08 pascal (35.7 ksi)

The similarity of these results is due to the changes in response and decreases in spectral acceleration between the two cases. In case 1, mass participation is low but system frequency is near spectral peaks and damping values are low (1/2% convective and 3% impulsive). In case 2, the participating mass is nearly twice as great, however, due frequency response increase and higher damping, the acceleration is about 50% less.

CONCLUSION

The conclusions of this work can only be considered applicable to "soft" soil sites (structure underlain by soil to depths greater than 75m and shear wave velocities between 167 m/sec to 488 m/sec in the surface layer). A definite reduction in the in-structure response can be anticipated for structures below ground and inter-tank effects are very small. Amplification of the free field spectra may be anticipated for tanks at grade, however, it is believed that this issue requires further study. The use of the free field motion for input to the fluid structure interaction analysis model cannot be assumed to be enveloping. Unless design margins are extremely small, the effects of dynamic lateral earth pressure may be considered negligible for both individual tanks and tanks in close proximity.

The effect of viscosity on the fluid structure interaction is not yet completely understood but it appears that some bounds could be placed on its behavior. It appears that the simplistic approach for the high viscosity case utilized in this analysis does not result in more restrictive or demanding structural design than those resulting from the use of the most current methods for low viscosity fluids.

These tanks were not originally designed considering seismic loads. In the course of this analysis, some observations were made about the design details that could have cost effective impact on new designs. Since concrete vaults are required for both shielding and as a secondary confinement barriers, integration of steel and concrete designs that utilized the concrete vaults as a top anchor for the tank has some benefit. The consequences of slosh impact on the roof is negligible since load would be carried through the vault. The tank can serve as the form work for the vault top slab concrete pour. By constraining the tank between the top and bottom slabs of the vault, heavy anchorage and local reinforcing at the bottom anchorage is not necessary. Only shear connection is required and as demonstrated in this case it was required at the top.

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REFERENCES

1. JOHN O. HALLQUIST, et al, DYNA3D, Nonlinear Dynamic Analysis of Structures in Three Dimensions, , UCID-19592, Lawrence Livermore National Laboratory, CA.
2. JOHN LYSMER, et al, SASSI, A System for Analysis of Soil-Structure Interaction, University of California, Berkeley, CA, 1981.
3. SHAKE, A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites, B. Schnabel, et al, EERC-72-12, University of California, Berkeley, CA.
4. A. S. VELETSOS and J. Y. YANG, Dynamics of Fixed-Base Liquid Storage Tanks, Proceedings of U.S./Japan Seminar for Earthquake Engineering Research with Emphasis on Lifeline Systems, Tokyo, Japan, November 1976.
5. A. S. VELETSOS and J. Y YANG, Earthquake Response of Liquid Storage Tanks, Second Proceedings for Advances in Civil Engineering through Engineering Mechanics, Raleigh, NC, May 1977.
6. Guidelines for the Seismic Design of Oil and Gas Pipeline Systems, ASCE.
7. A. S. VELETSOS and P. SHIVAKUMAR,On Dynamics of Liquid Containing Cylindrical Tanks,
8. Y. TANK and H. T. TANG, Dynamic Response of Anchored Steel Tanks, A. S. Veletsos, P.Shivakumar.
9. M. ZASLAWSKY and W. KENNEDY, Comparison of DYNA3D to Approximate Solutions for Tanks Subjected to Seismic Loading, WSRC.