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Comparison of response results for liquid-structure interaction analysis and simplified analysis procedures for seismic analysis of liquid storage tanks

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1. Introduction

A liquid-structure interaction analysis program for seismic analysis of cylindrical liquid storage tanks was developed in [1]. The program has been set up as two separate programs, TANKMODES, which calculates the modes of vibration of a tank, and TANKRESP, which makes use of data files stored from the TANKMODES run and calculates the response of the tank structure using the response spectrum analysis method. The TANKMODES and TANKRESP programs do not consider sloshing of the liquid surface, but it is straightforward to consider this effect in a separate analysis.

TANKMODES was tested in [1]. The next stage is to test TANKRESP, and it was decided to do this by comparing response results produced by the program with results obtained from two simplified analysis procedures that are specified in the nuclear industry, one given in the ASCE 4 Standard commentary [2], and the other in the BNL 52361 report [3]. The BNL 52361 report was found in [1] to give accurate results for the first mode natural frequency of a broad tank in both horizontal and vertical vibration directions, which suggests that it has some potential to be used for verification of TANKRESP. The simplified analysis procedures assume the first mode dominates the seismic response of the tank, which is probably a reasonable assumption, and so TANKRESP is run with only one mode considered in the analysis.

This study adopts the same test problems that were used in [1], broad and tall cylindrical steel tanks that are completely filled with water with key dimensions as shown in Figure 1 below.

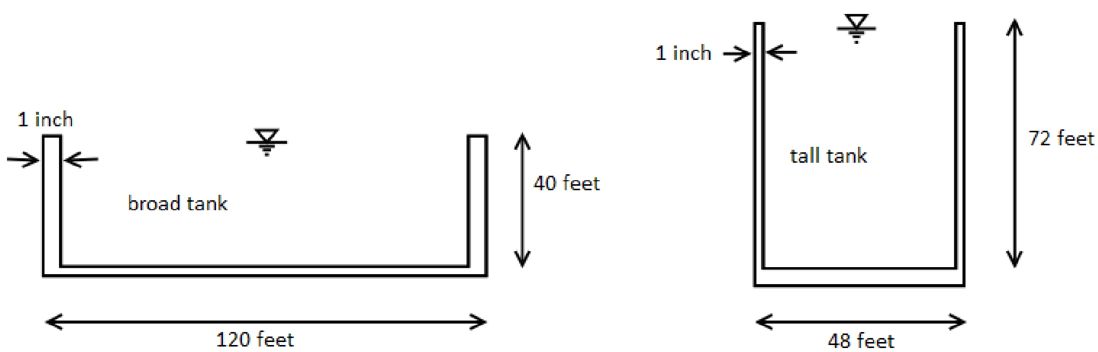

Figure 1 Details of broad and tall tanks used as test problems

The tanks are subject to a 1g spectral acceleration input at the fundamental horizontal or vertical natural frequency of the tank.

The simplified analysis procedures use static analysis with a specified impulsive pressure distribution. TANKRESP does not have a capability to perform static analysis, but this capability is available in the axisymmetric fourier harmonic analysis program ASHSD2 [4]. So ASHSD2 has been used to carry out the simplified impulsive pressure analysis.

2 Simplified response analysis procedures

2.1 ASCE 4 procedure for broad and tall tanks

This procedure is given in the ASCE 4 Standard commentary and covers both broad and tall tanks. For the horizontal vibration direction (harmonic 1), the impulsive pressure P_1 acting on the tank wall is:

$$P_1 = \frac{W_1 X_1 Sa_1}{0.68\, D\, H^2} \qquad \text{for depth} \geq 0.15\ H \text{ below the liquid surface}$$

where H is liquid height, D is tank diameter, W_1 is the impulsive liquid weight, X_1 is an effective distance above the tank base where the impulsive weight can be regarded as acting, and Sa_1 is the spectral acceleration in g units at the first horizontal natural frequency of the tank (taken as 1.0g for the test problem).

The impulsive pressure varies linearly from zero at the liquid surface to the P_1 value at a depth of 0.15H.

For a broad tank with $D/H \geq 1.3333$, the impulsive fluid weight W_1 relates to the total fluid weight W_T as:

$$\frac{W_1}{W_T} = \frac{\tanh(0.866\ D/H)}{0.866\ D/H}$$

and $X_1 = 0.375\ H$

For a tall tank with $D/H < 1.3333$, the impulsive fluid weight W_1 relates to the total fluid weight W_T as:

$$\frac{W_1}{W_T} = 1.0 - 0.218\ (D/H)$$

and $X_1 = 0.50\ H - 0.095\ D$

For the vertical vibration direction (harmonic 0), the impulsive pressure P_V acting on the tank wall is assumed to have the same form as a hydrostatic pressure distribution:

$$P_V = Sa_v\, \rho\, y$$

where ρ is the liquid weight density, y is the depth below the liquid surface and Sa_v is the spectral acceleration in g units at the first vertical natural frequency of the tank (taken as 1.0g for the test problem).

The above procedure, adopted by the ASCE 4 Standard since 1986, was originally specified in a 1980 report [5], which recommended changes to seismic design-related sections of the US Nuclear Regulatory Commission's Standard Review Plan, and the procedure has been essentially accepted by the USNRC since 1989.

2.2 BNL 52361 procedure for broad tank

The BNL 52361 report [3] is limited to broad tanks which have a D/H ratio ≥ 2.0. For the horizontal vibration direction (harmonic 1), the impulsive pressure p_i acting on the tank wall is given by equation 4.2:

$$p_i\,(\eta_l,\theta,t) = c_i\,(\eta_l)\,\rho_l\,R\,A_i\,(t)\cos(\theta)$$

where ρ_l is liquid weight density, A_i (without the time dependence) can be interpreted as the spectral acceleration in g units at the first horizontal natural frequency of the tank (taken as 1.0g for the test problem), η_l is the vertical distance above the tank base as a fraction of the liquid height H_l, R is the tank radius, θ is the angle around the circumference and $c_i\,(\eta_l)$ is a dimensionless coefficient.

Table 4.1 in [3] provides $c_i\,(\eta_l)$ values for ten H_l/R ratios at eleven equally spaced vertical locations η_l on the tank wall. Formulae are also provided in [3] to calculate $c_i\,(\eta_l)$ for any desired η_l location and H_l/R ratio (equations 4.4, 4.5 and 4.7), but for the test problem it was preferred to use the Table 4.1 locations and interpolate $c_i\,(\eta_l)$ for the required H_l/R ratio.

For the vertical vibration direction (harmonic 0), the impulsive pressure p_v acting on the tank wall is given by equation 4.52:

$$p_v\,(\eta_l) = 0.8\,[\cos(\tfrac{1}{2}\,\pi\,\eta_l)]\,\rho_l\,H_l\,(Sa)_V$$

where $(Sa)_V$ is the spectral acceleration in g units at the first vertical natural frequency of the tank, and is taken as 1.0g for the test problem.

The vertical impulsive pressure distribution is assumed to have a quarter cosine wave shape rather than the hydrostatic pressure distribution shape that is assumed in ASCE 4.

3 Comparison of response results

3.1 Response analysis models

In order to run the broad and tall tank test problems for a seismic response analysis, it was decided to use a greater number of shell elements than was adopted in [1] for the initial TANKMODES analysis to provide more detailed results near the tank base. The broad tank was modelled using 80 axisymmetric shell elements and a 80 x 80 liquid finite element mesh. The tall tank was modelled using 160 axisymmetric shell elements and a 60 x 160 liquid finite element mesh. In TANKRESP a single mode response analysis has been used (with no modal response combination), and the program is set up to retain the signs of the responses when single mode analysis is specified.

To implement the two simplified static analysis procedures, ASHSD2 models of the broad and tall tanks were used. The ASHSD2 models have the same number of axisymmetric shell elements as the TANKRESP models - 80 for the broad tank and 160 for the tall tank.

3.2 Comparison of TANKRESP with ASCE 4 procedure for broad tank

Response results from TANKRESP are compared with results from the ASCE 4 procedure for the broad tank in Figures 2a to 2e for the horizontal vibration direction (harmonic 1) and in Figures 3a to 3c for the vertical vibration direction (harmonic 0) below. The TANKRESP results are labelled 'LSI' in the figures.

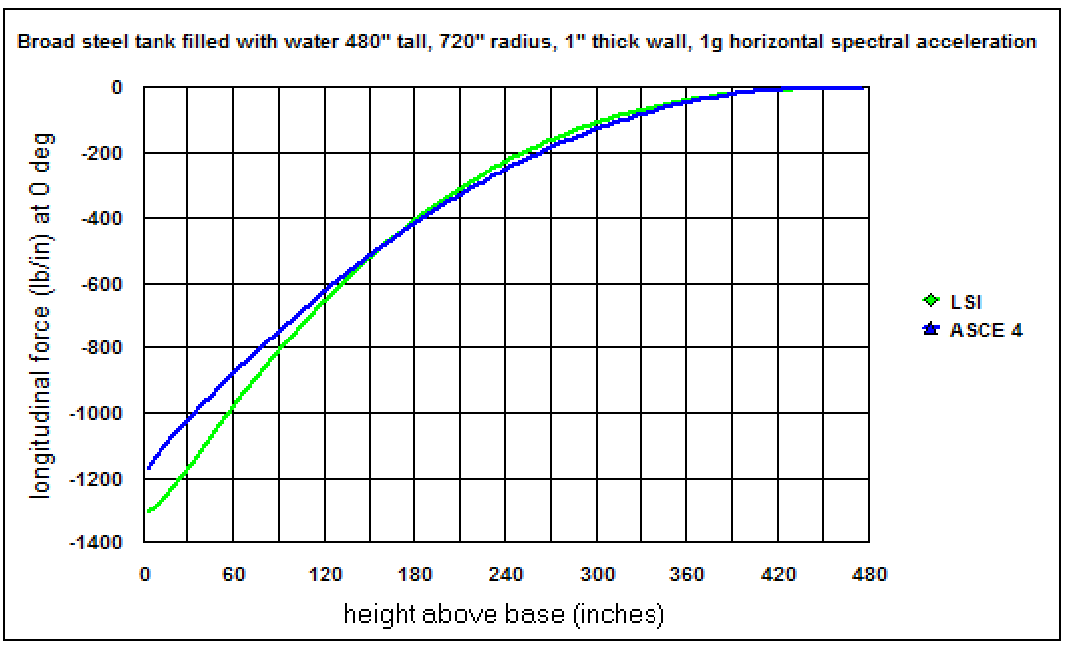

Figure 2a

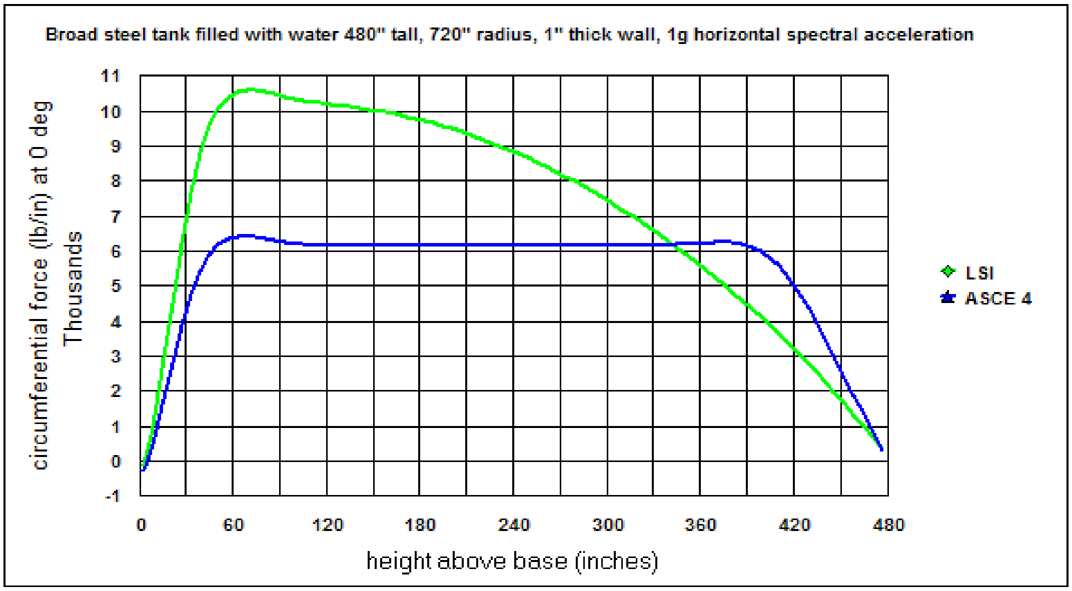

Figure 2b

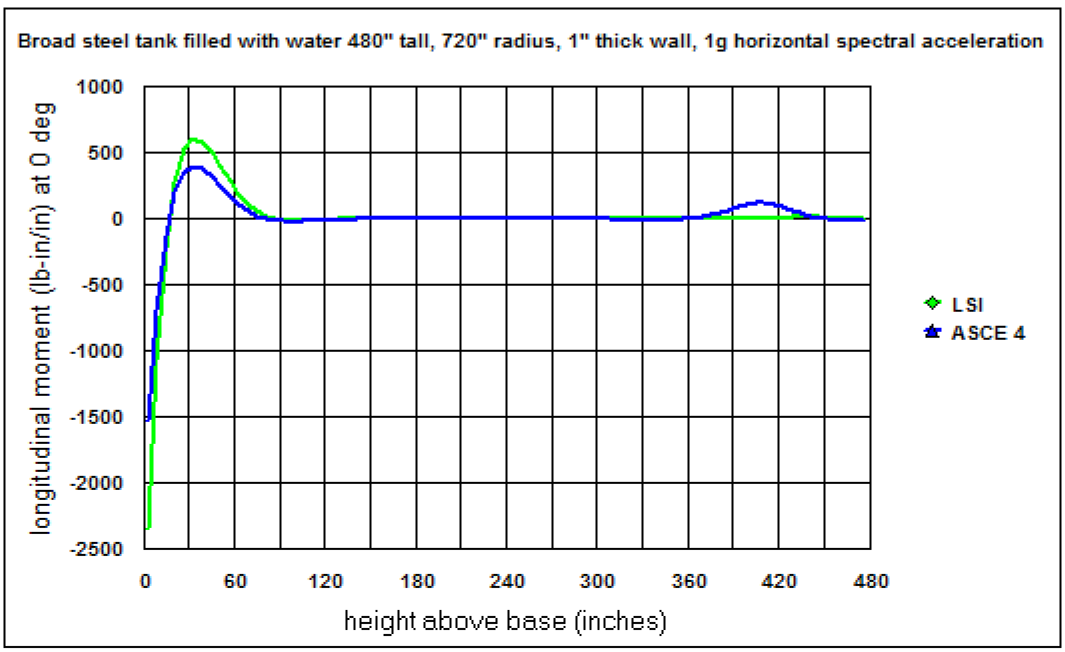

Figure 2c

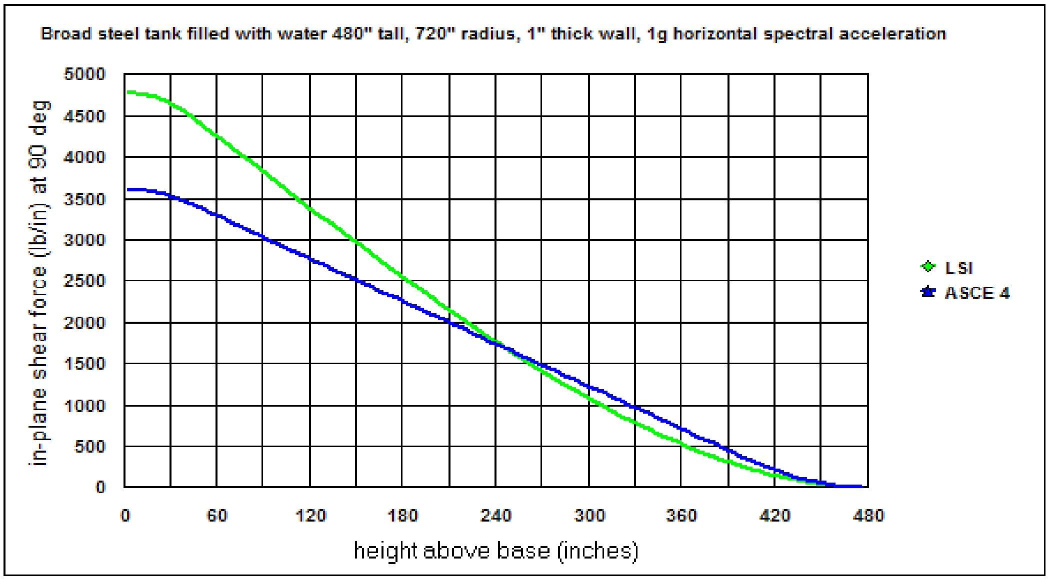

Figure 2d

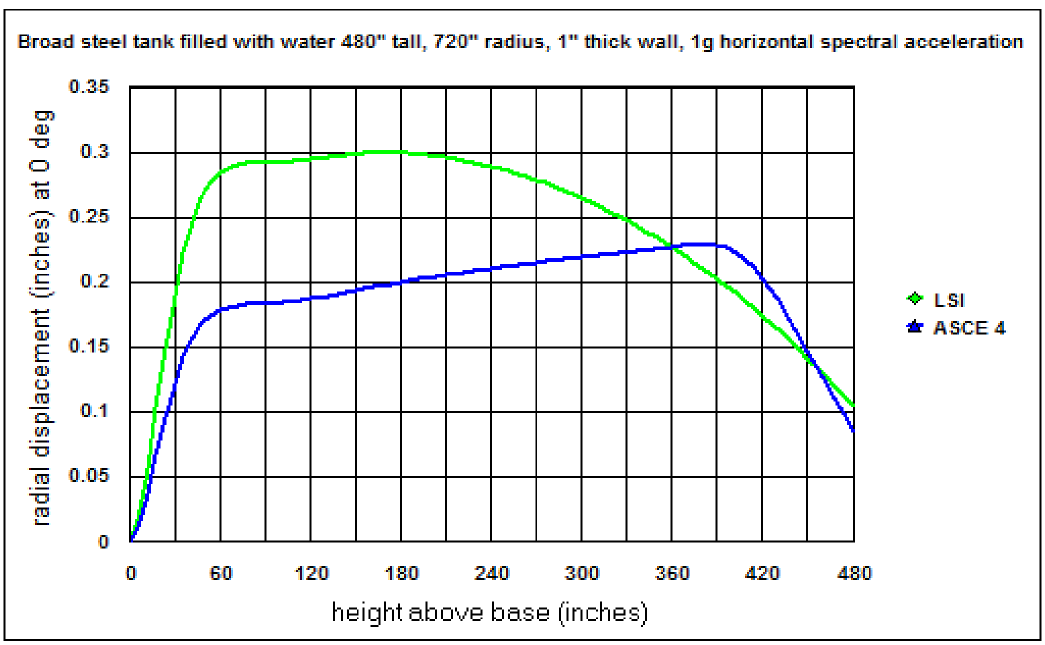

Figure 2e

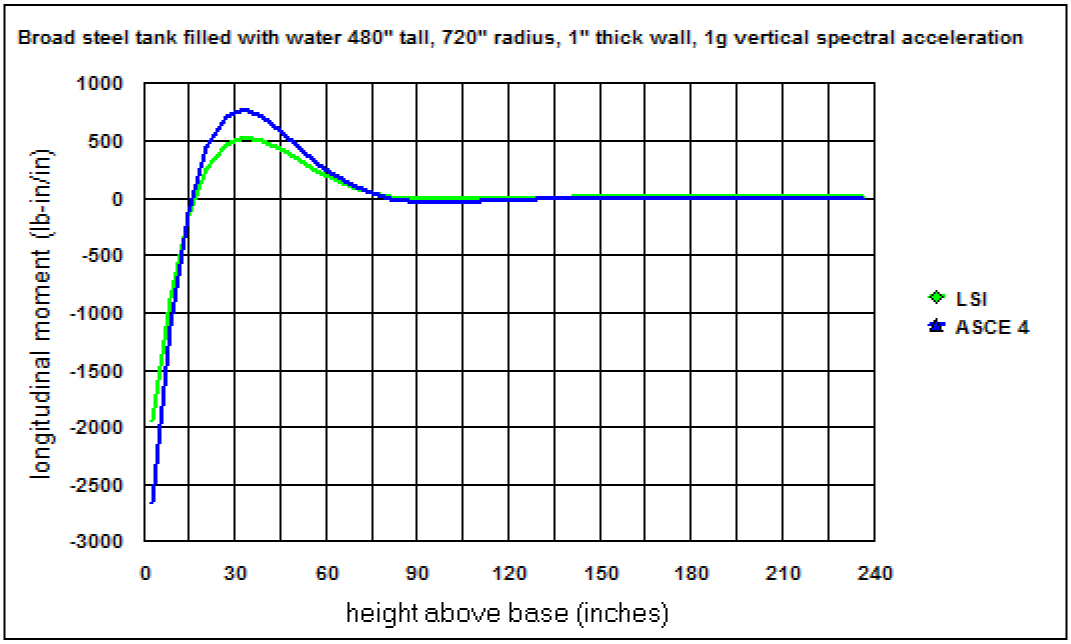

Figure 3a

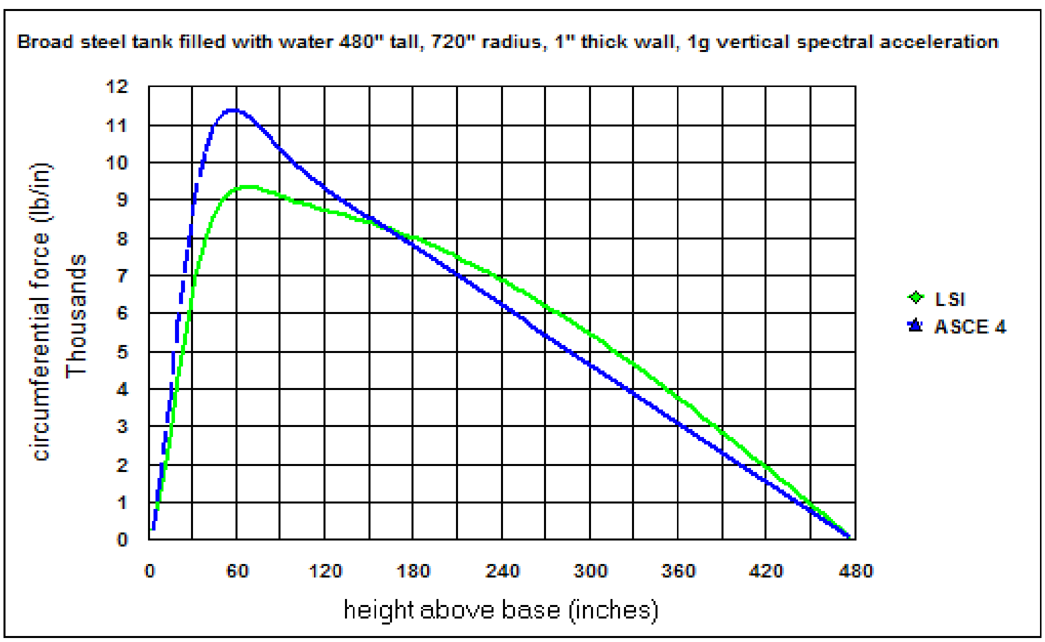

Figure 3b

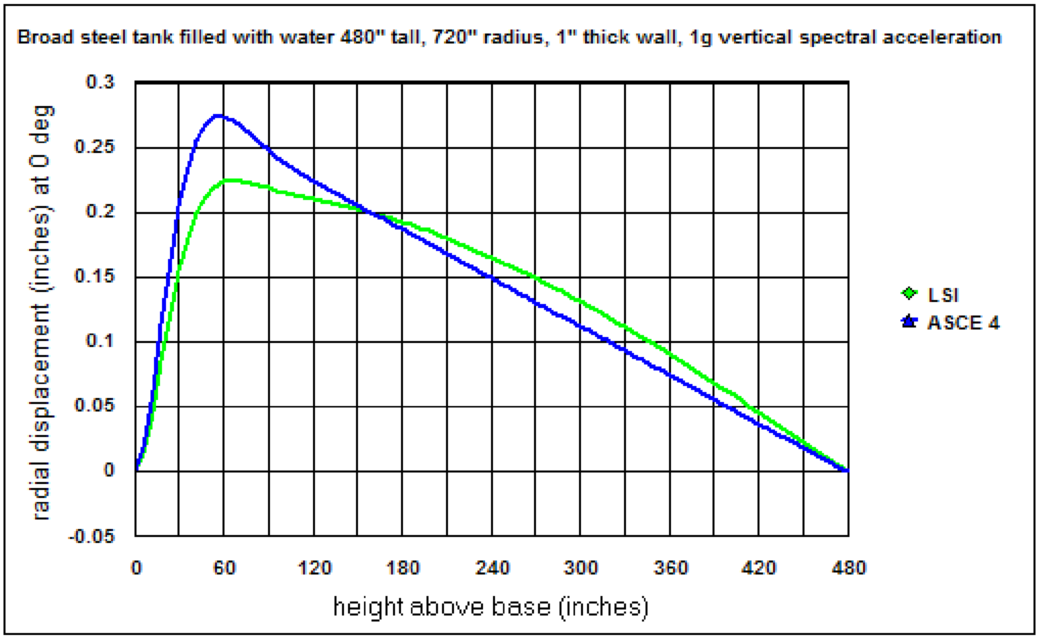

Figure 3c

For the horizontal vibration direction, the ASCE 4 procedure is slightly unconservative for longitudinal force, but significantly unconservative for response quantities like circumferential force, in-plane shear force and radial displacement compared with TANKRESP.

For the vertical vibration direction, the ASCE 4 procedure tends to produce conservative responses compared with TANKRESP.

3.2 Comparison of TANKRESP with ASCE 4 procedure for tall tank

Response results from TANKRESP are compared with results from the ASCE 4 procedure for the tall tank in Figures 4a to 4e for the horizontal vibration direction (harmonic 1) and in Figures 5a to 5c for the vertical vibration direction (harmonic 0) below. The TANKRESP results are labelled 'LSI' in the figures.

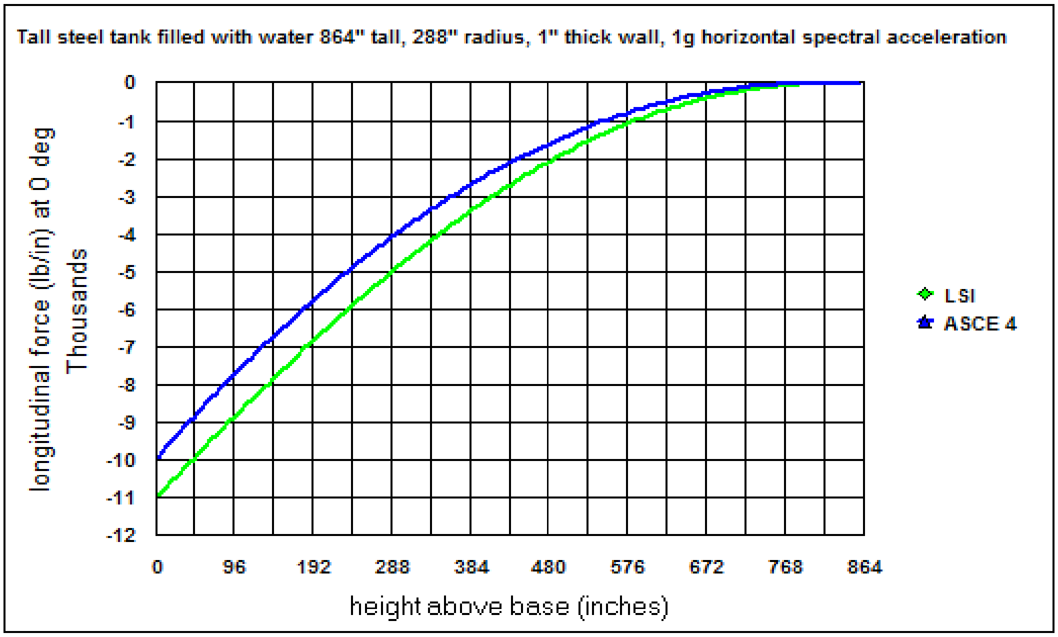

Figure 4a

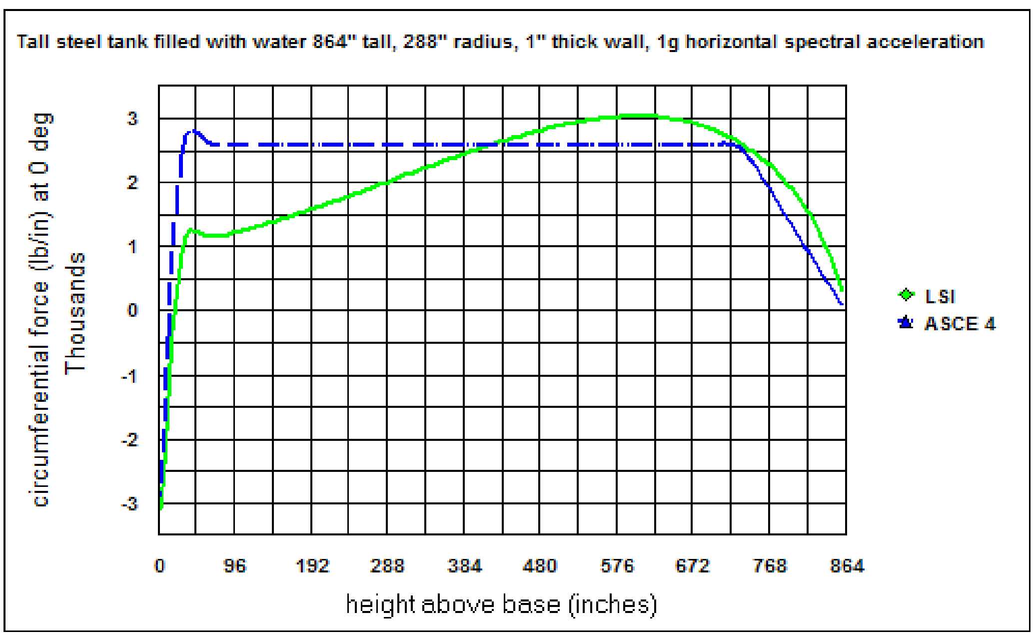

Figure 4b

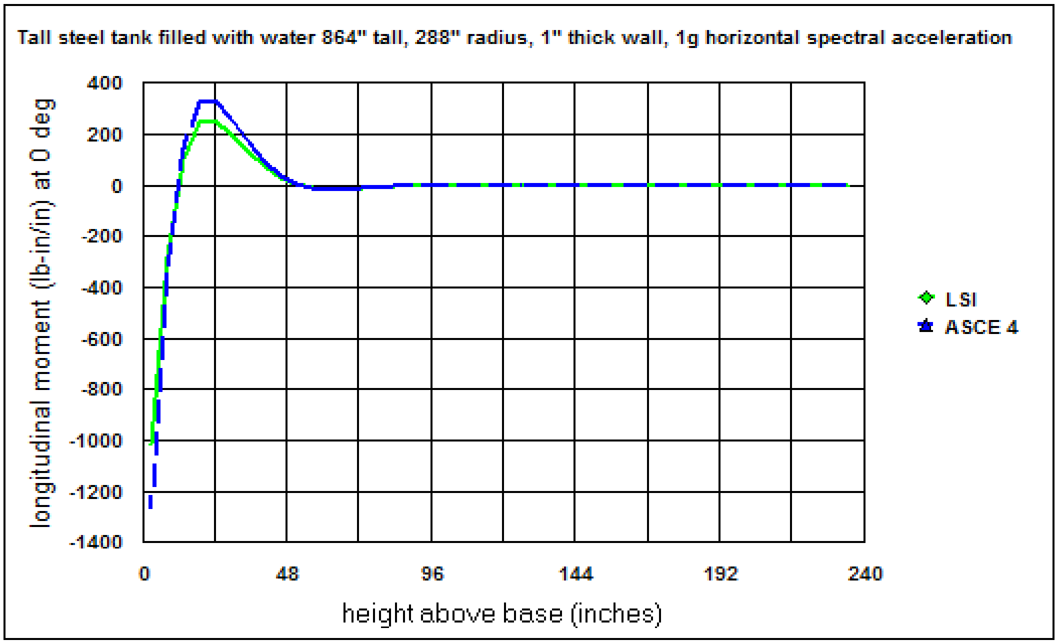

Figure 4c

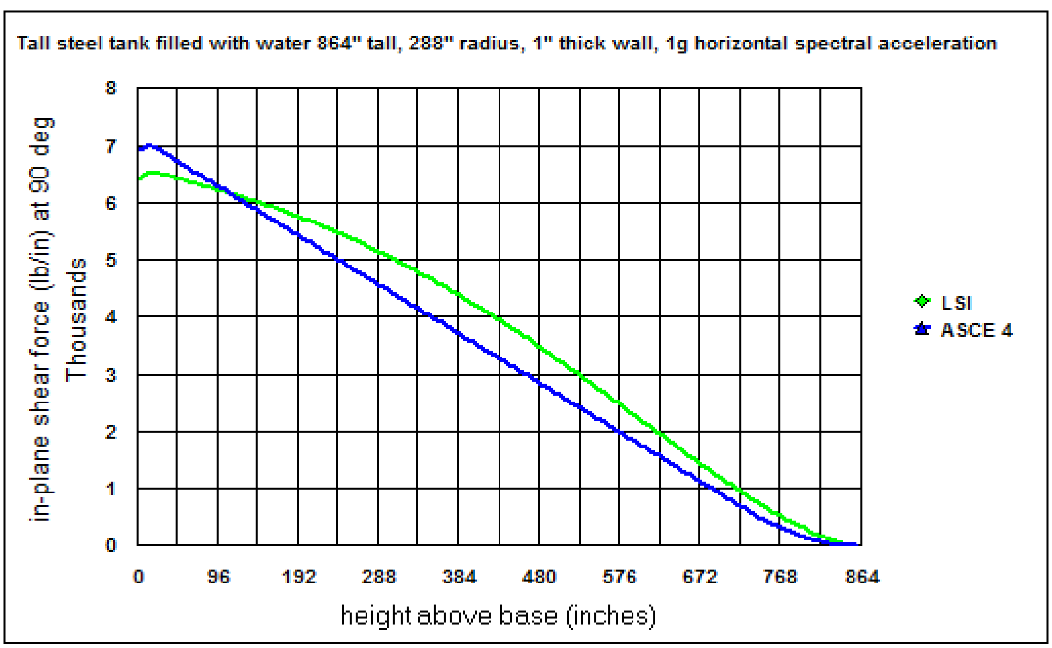

Figure 4d

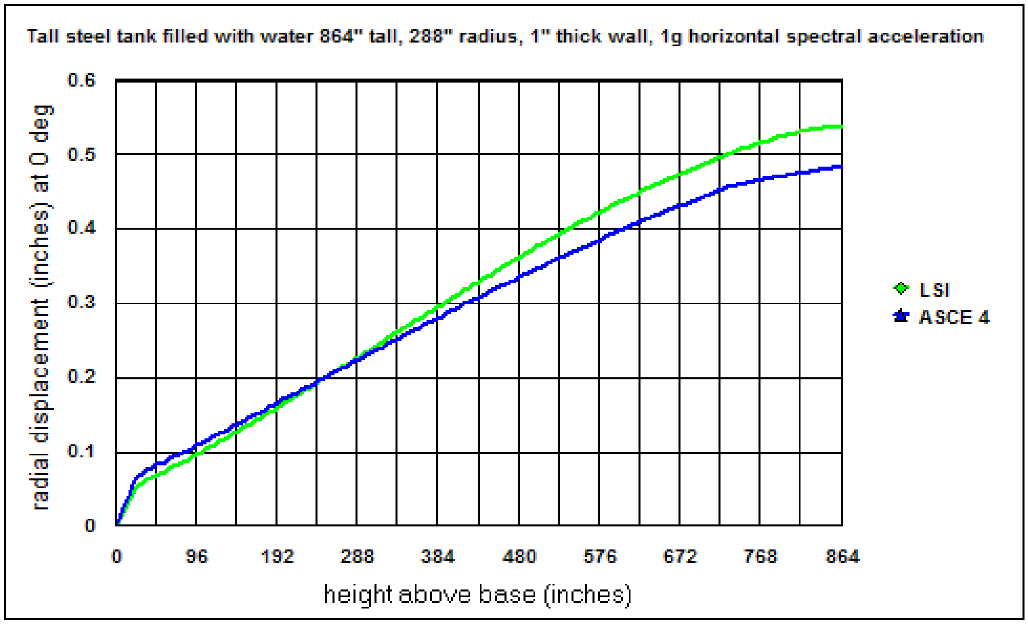

Figure 4e

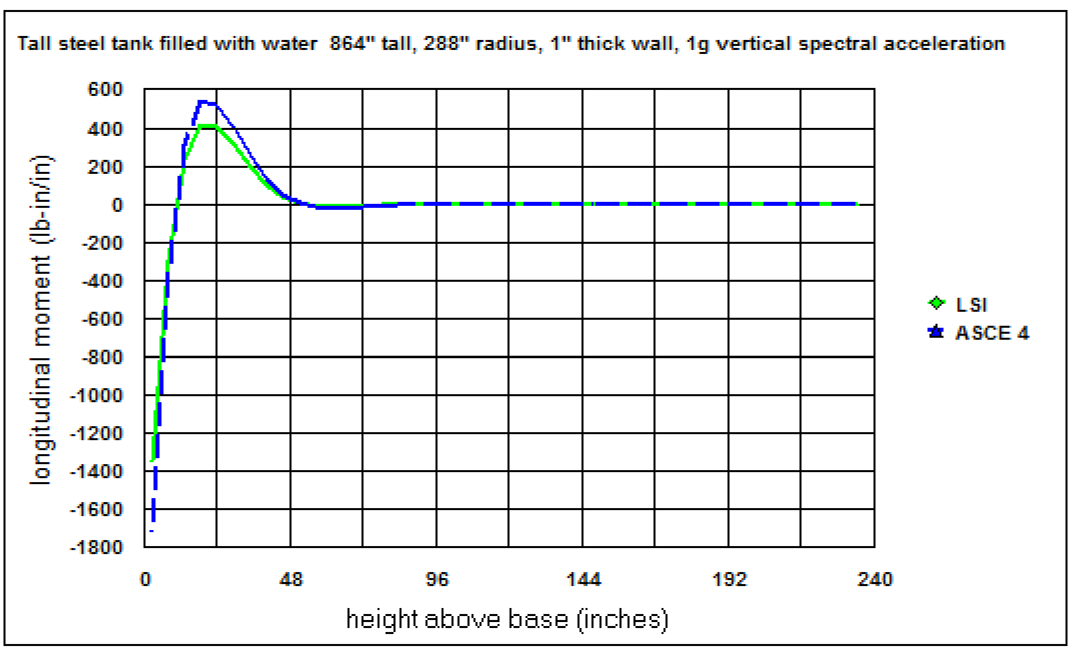

Figure 5a

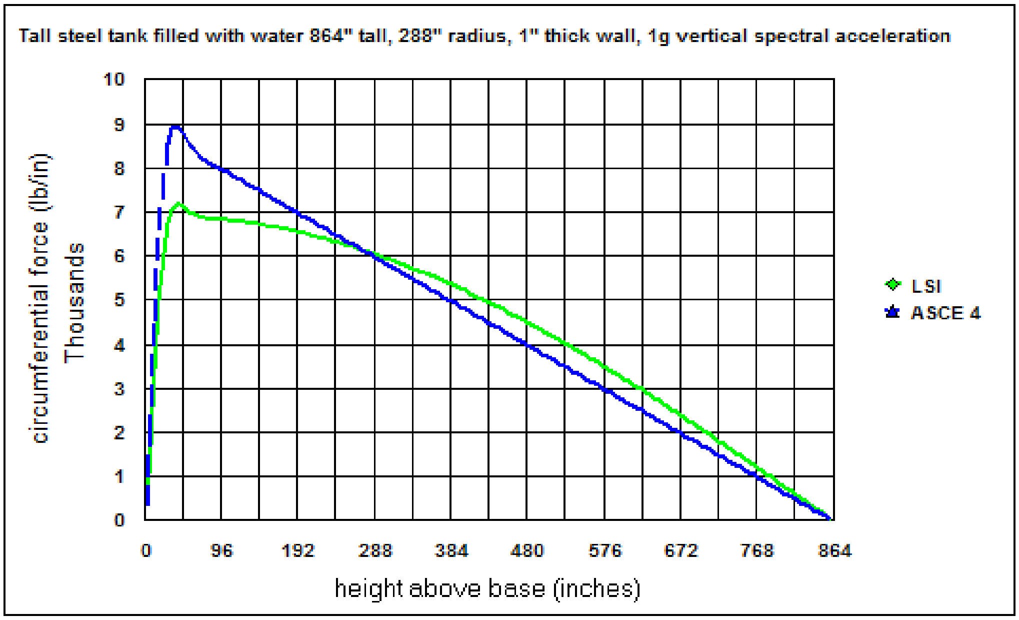

Figure 5b

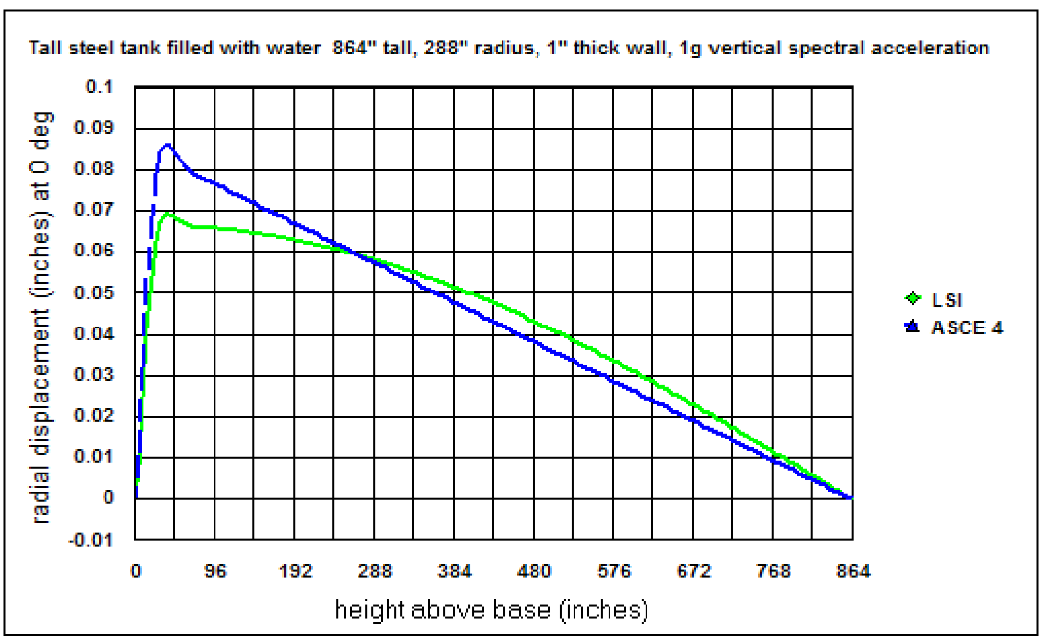

Figure 5c

For the horizontal vibration direction, the ASCE 4 procedure tends to produce conservative or slightly unconservative responses compared with TANKRESP. The

ASCE 4 procedure seems to perform better for a tall tank than a broad tank in comparison with TANKRESP.

There are some differences in the circumferential (or hoop) force distribution for broad and tall tanks. TANKRESP predicts that the peak circumferential force occurs in the upper half of the tank for a tall tank. There is also a substantial variation in the circumferential force near the base of the tank for a tall tank, which includes a change in sign of the response (the circumferential force is zero at the tank base).

For the vertical vibration direction, the ASCE 4 procedure tends to produce conservative responses compared with TANKRESP.

3.2 Comparison of TANKRESP with BNL 52361 procedure for broad tank

Response results from TANKRESP are compared with results from the BNL 52361 procedure for the broad tank in Figures 6a to 6e for the horizontal vibration direction (harmonic 1) and in Figures 7a to 7c for the vertical vibration direction (harmonic 0) below. The TANKRESP results are labelled 'LSI' in the figures.

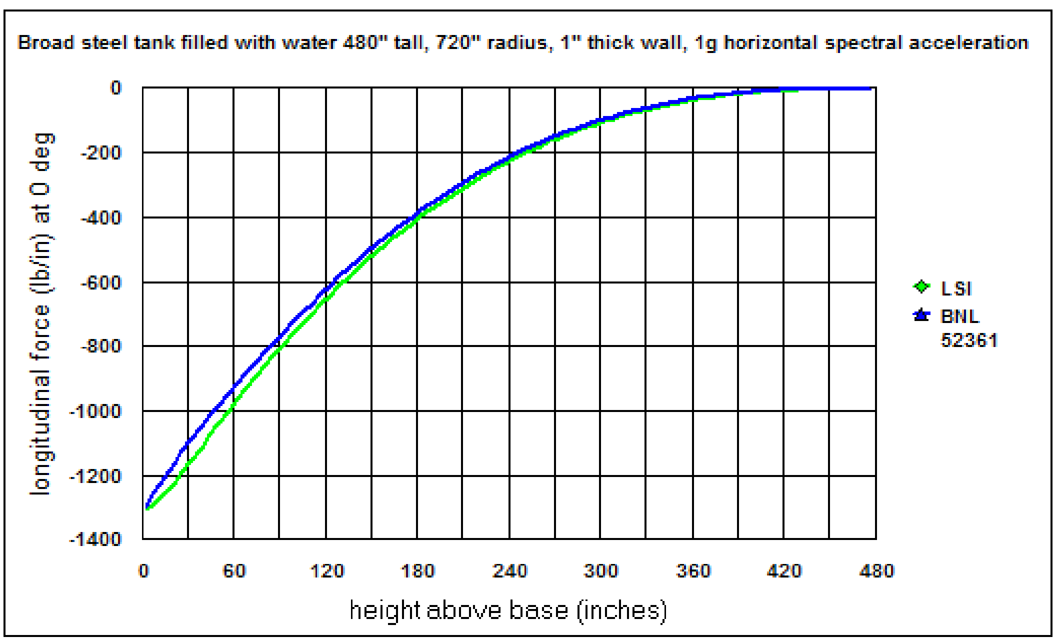

Figure 6a

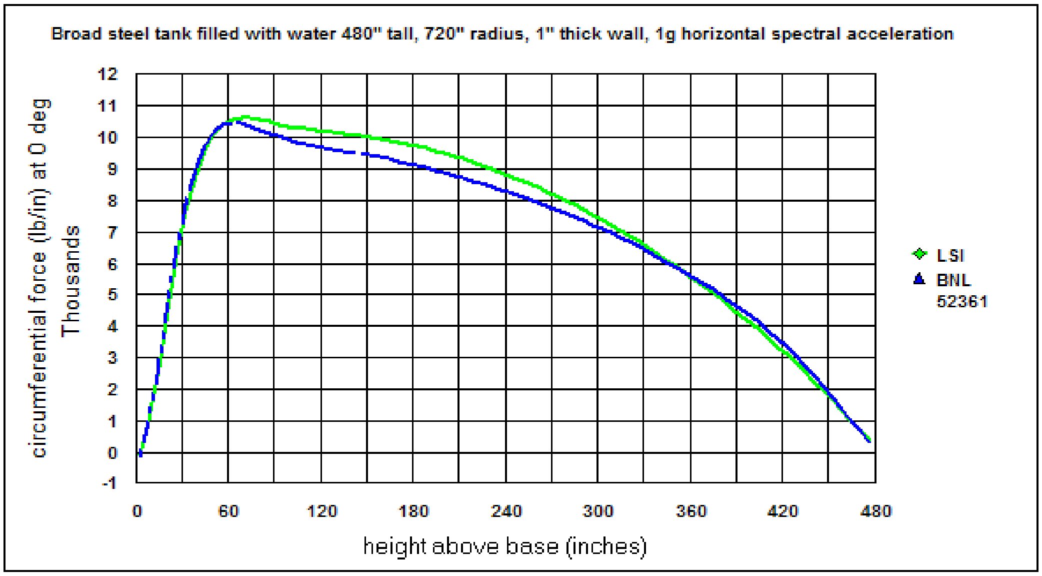

Figure 6b

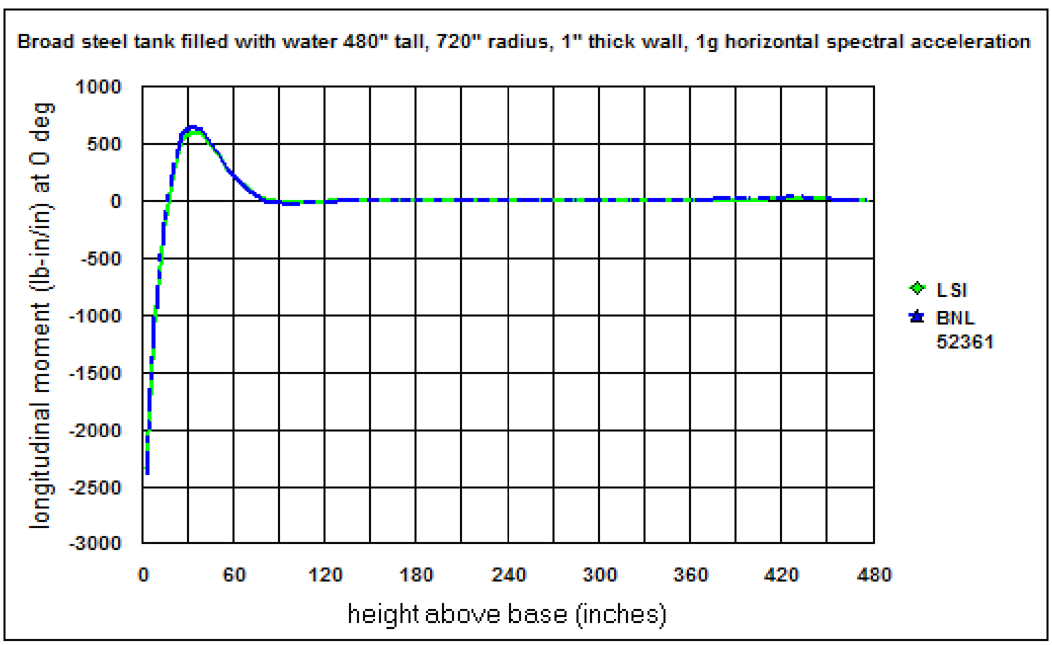

Figure 6c

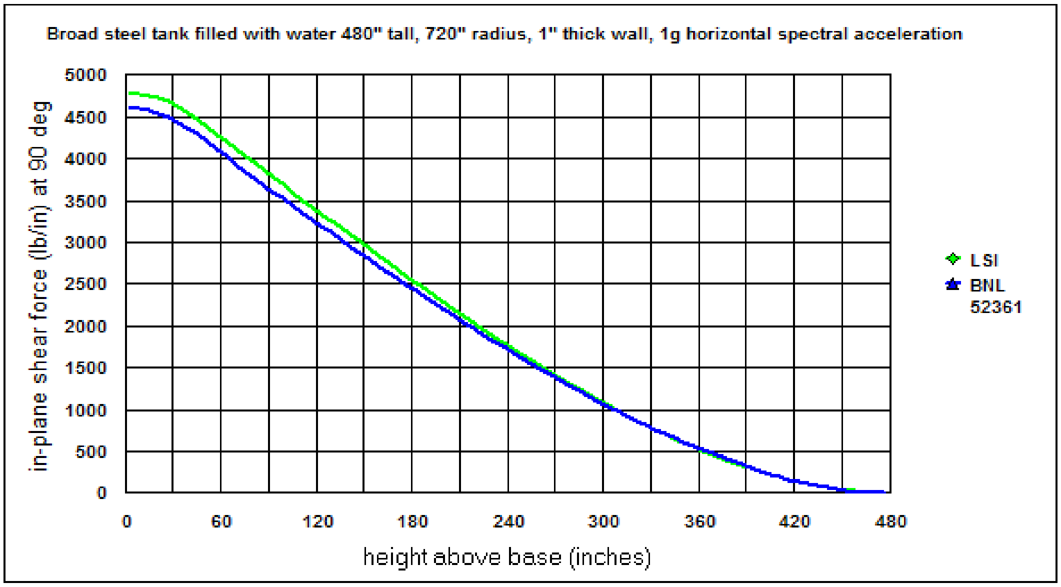

Figure 6d

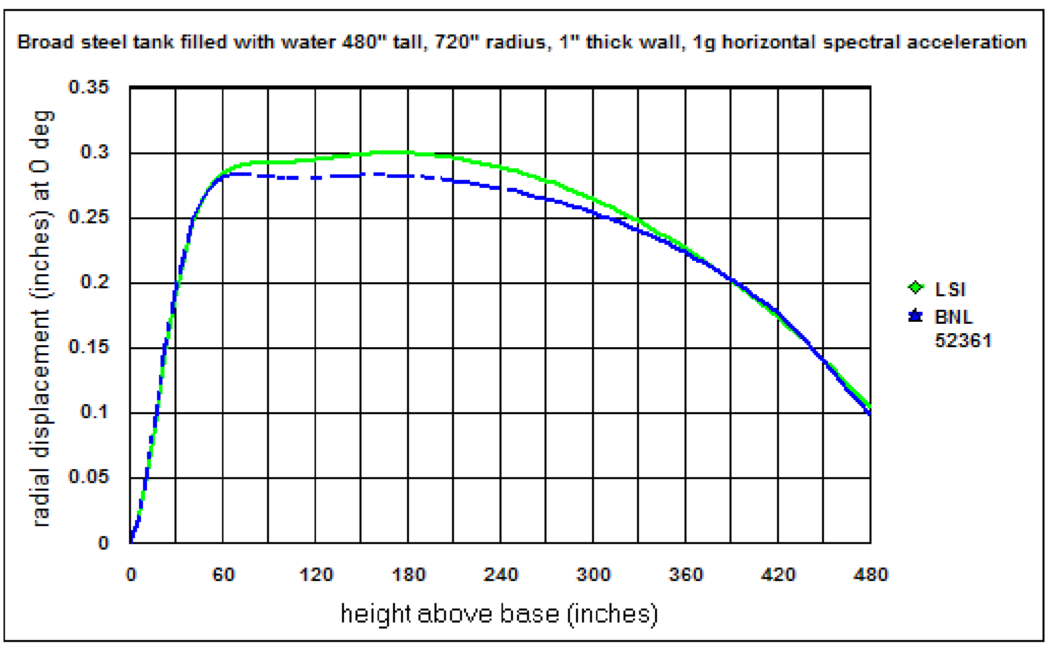

Figure 6e

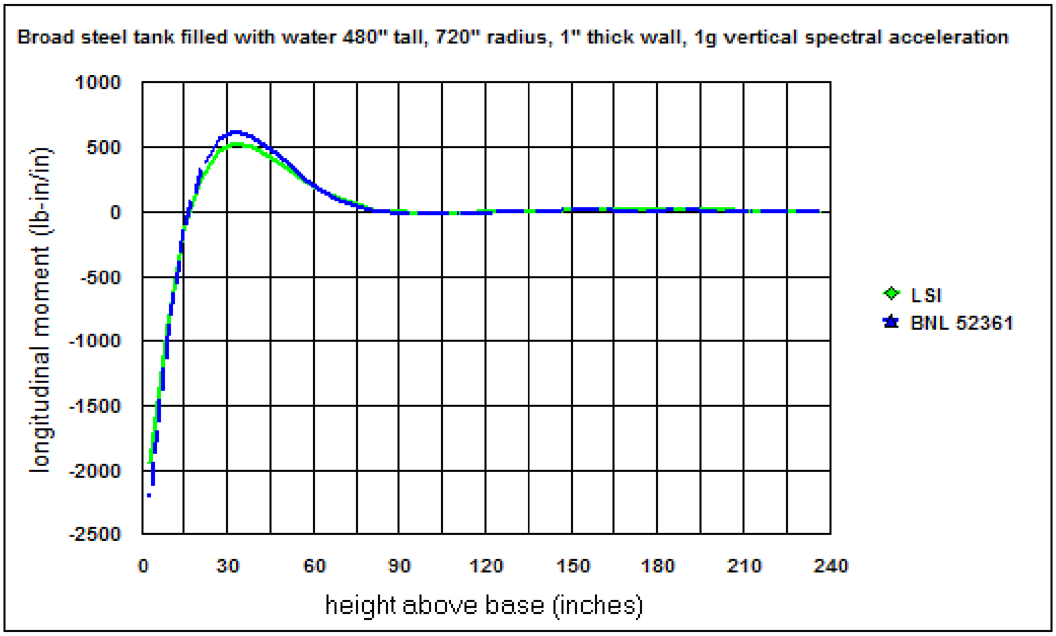

Figure 7a

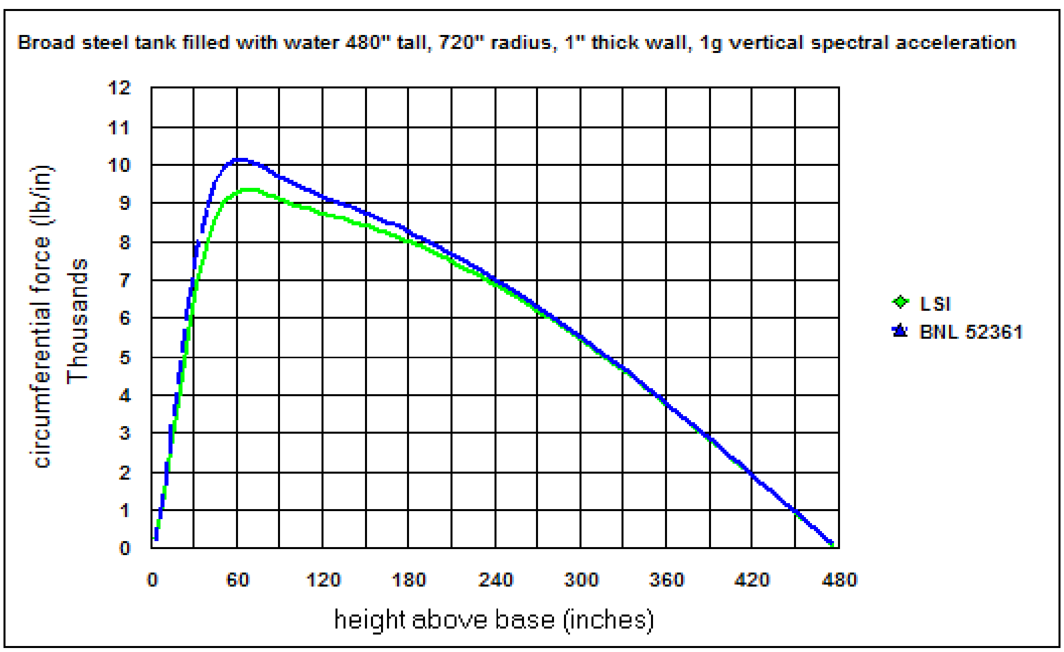

Figure 7b

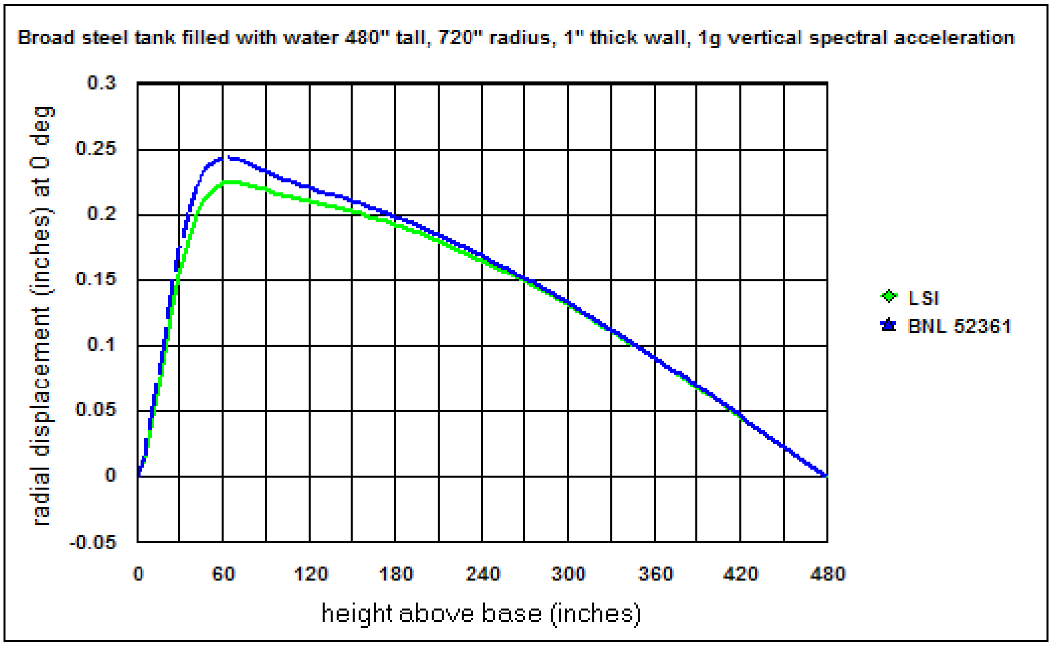

Figure 7c

For both the horizontal and vertical vibration directions, the BNL 52361 procedure gives response results that show good agreement with TANKRESP. The comparison suggests that it would be better to use the BNL 52361 procedure over the ASCE 4 procedure for a broad tank.

4 Conclusions

1 The TANKRESP program, which carries out a response spectrum analysis of a cylindrical liquid storage tank, has been tested against two simplified impulsive pressure analysis procedures for seismic analysis that are specified in the nuclear industry, the ASCE 4 procedure [2] and the BNL 52361 procedure [3], for broad and tall tank geometry cases.

2 TANKRESP shows good agreement with the BNL 52361 procedure for response results associated with both horizontal and vertical vibration directions for the broad tank (BNL 52361 is limited to broad tanks).

3 The ASCE 4 procedure shows worse agreement with TANKRESP than the BNL 52361 procedure. For the horizontal vibration direction, ASCE 4 tends to produce significantly unconservative response results compared with TANKRESP for a broad tank, but for a tall tank the comparison is better, tending to produce conservative or slightly unconservative response results compared with TANKRESP. For the vertical vibration direction, ASCE 4 tends to produce conservative response results compared with TANKRESP for both broad and tall tanks.

5 References

[1] Gardner D J, "Development of liquid-structure interaction analysis program for seismic analysis of liquid storage tanks", April 2020

[2] ASCE Standard ASCE/SEI 4-16, "Seismic analysis of safety-related nuclear structures", 2017

[3] Bandyopadhyay K, Cornell A, Constantino C, Kennedy R, Miller C, Veletsos A, "Seismic design and evaluation guidelines for the Department of Energy high-level waste storage tanks and appurtenances", Brookhaven National Laboratory report BNL 52361, Oct 1995

[4] Ghosh S, Wilson E, "Dynamic stress analysis of axisymmetric structures under arbitrary loading", Earthquake Engineering Research Center report EERC 69-10, Sept 1969, revised Sept 1975

[5] Coats D W, "Recommended revisions to Nuclear Regulatory Commission seismic design criteria", NUREG/CR-1161, May 1980