COMPARISON BETWEEN SEISMIC RESPONSES OF ANCHORED AND UNANCHORED CYLINDRICAL STEEL TANKS

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ABSTRACT:

Many above-ground cylindrical steel tanks have borne serious damages during the past earthquakes. Therefore understanding and forcasting their seismic behavior have attracted numerous researchers.

These tanks are mainly classified into two types, i.e. anchored and unanchored. Of course a large number of existing tanks in oil and petrochemical industries are of the second type which has been more susceptible to damage in the past earthquakes. The seismic responses of above-ground liquid-filled steel tanks have been investigated using comprehensive finite element techniques. Both fluid-structure and soil-structure interactions have been employed in order to take the actual behavior of structure into account. In numerical study, finite element models have been used for three tanks with height to diameter ratios (H/D) of 0.33, 0.75 and 1.5, in which considering a liquid level of 90% of the height of cylinder, in an attempt to compare between seismic responses of unanchored and anchored tanks. Several factors are involved in the analysis of such tanks due to uplifting, material yielding, soil-tank interaction and large-amplitude free surface sloshing. It has been shown that the effects of the above mentioned factors for tanks of the two kinds, differ from each other. For instance in unanchored tanks, uplifting reduces the hydrodynamic pressures, whereas this phenomenon does not occur in anchored tanks. Also for broad tanks, both anchored and unanchored types show almost identical free surface sloshing, whereas it should be noted that this is not the case with tall tanks which appear to be more sensitive to sloshing phenomenon.

KEYWORDS: Cylindrical steel tanks, Unanchored & anchored, uplifting, sloshing, fluid-structure & soil-structure interactions

1. INTRODUCTION

Following rigorous damage in liquid storage tanks during strong earthquake like 1964 Alaska earthquake, researchers believed that flexibility of tanks can be important for designation of dynamic responses. Veletsos and Yang [1], Haroun and Housner [2], among many others, taken into consideration the effects of fluid-structure and fluid-structure-soil interactions in evaluation of seismic performance of fully anchored tanks. Also Al-zeiny [3] investigated the effects of different factors on dynamic responses of unanchored tanks.

In practice, many unanchored tanks are supported directly on flexible soil foundations. When subjected to earthquake ground shaking, these tanks uplift on one side and penetrate their flexible foundation on the opposite side. Malhotra [4] investigated that such tanks have sustained damage in the form of at least four categories: (1) the failure of the piping connections to the wall, caused by large base uplifting; (2) rupture at the plate-shell junction, caused by excessive joint stresses; (3) buckling of the tank wall, caused by large axial compressive stresses; and (4) failure of the soils underneath, caused by excessive foundation penetrations. Whereas, none of the above cases occur in anchored tanks. In this study, it has been considered fluid-structure-soil interaction too, but whereof fluid elements are susceptible to severe damage (disconvergency) in strong earthquakes like Kobe earthquake, comprehensive software using optimum mesh refining technique has been used for this specific problem while using of section control decreases to enough element damage.

2. FEM MODELING OF TANKS

For comprehensive assessment from earthquake performance, an updated software has been used to calculate the earthquake response of three storage tanks of different aspect ratios: The broad tank is 12 m high and has a radius of 18 m (H/D=0.33), The medium tank is 15 m high and has a radius of 10 m (H/D=0.75), and The tall tank is 21 m high, 7 m in radius. All three tanks have a shell and base plate thickness of 25 mm. The young's modulus of elasticity and yield stress of steel tank material are 210 Gpa and 214 Mpa, respectively. It is important to note that tank elements have been modeled using a four-nodes doubly curved shell element with reduced integration, hour-glass control, and finite membrane strain formulation [5].

3. LIQUID MODEL

In the problem of the hydrodynamic response of horizontally excited tank-liquid systems appears the impulsive and the convective actions, therefore sloshing phenomenon can be important. An effective method for modeling water in this case is to use a linear equation of state for the bulk response. For this problem the linear equation of state is used with a wave speed of 1500 m/s and density of 1000 kg/m^3 . This wave speed corresponds to a bulk modulus of 2.07 Gpa. In addition, water can be considered as incompressible and inviscid material.

4. SOIL MODEL

The yield criteria for this class of models are based on the shape of the yield surface in the stress-strain plane. The yield surface can have a linear form, a hyperbolic form, or a general exponent form. Soil layers are modeled using the linear form of the Drucker-Prager model having young's modulus of elasticity of 2.5 Gpa and possion's ratio of 0.29.

Soil elements experimentally is modeled in a distance of 2D (D=Diameter of tank) from the tank edge and D from the tank base. In discussion of liquid-structure-soil interaction has been used algorithm of contact between surfaces. In intersection surface of structure-soil, horizontal contact has been used in addition to vertical contact. Finite element meshes for the coupled soil-liquid-tank system of all three models are illustrated in Figures 1 to 3.

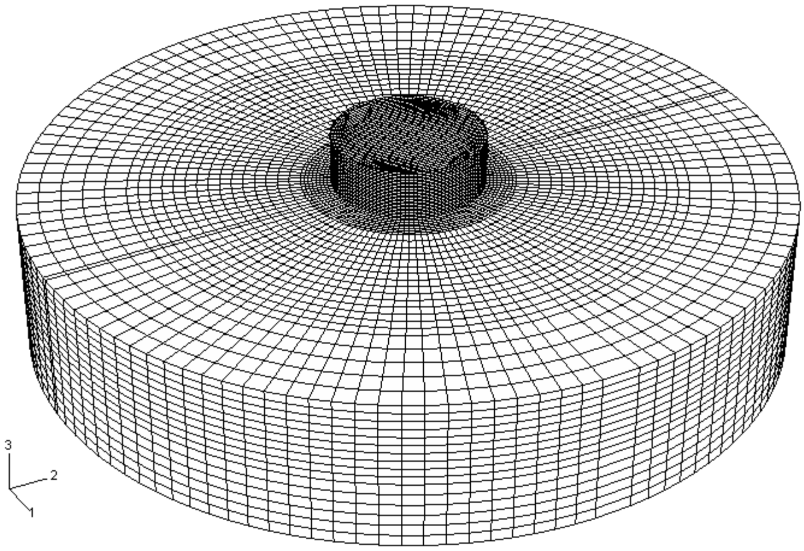

FIG.1. Finite element mesh for the coupled soil-liquid-broad tank system (H/D=0.33)

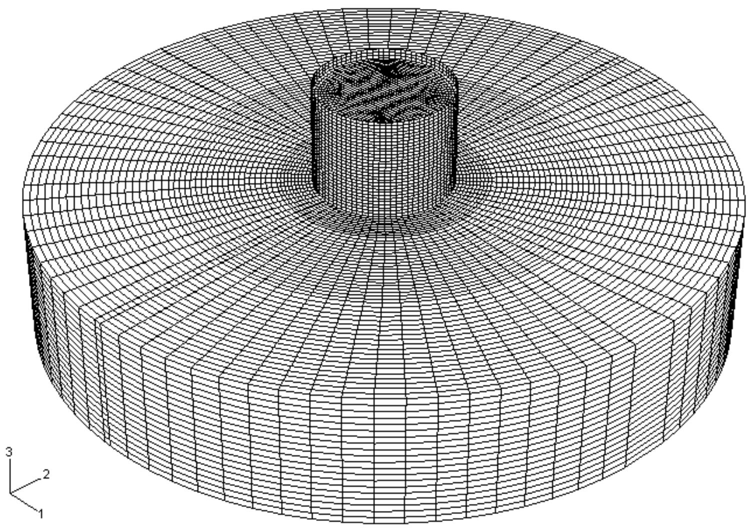

FIG.2. Finite element mesh for the coupled soil-liquid-medium tank system (H/D=0.75)

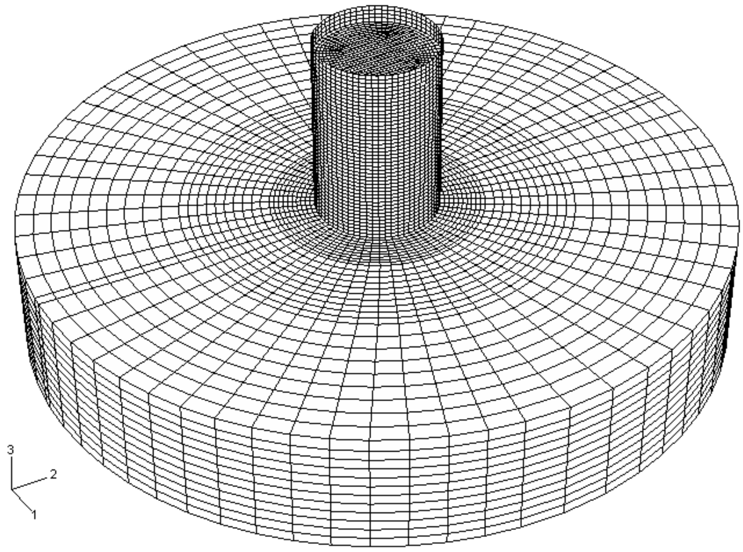

FIG.3. Finite element mesh for the coupled soil-liquid-tall tank system (H/D=1.50)

5. INPUT GROUND MOTIONS

Tanks were subjected to the following two different earthquake motions:
The record from the Northridge earthquake measured at the Arleta station site which has a peak ground acceleration of 0.344g, as shown in Figure 4. The second record has been chosen from the Kobe earthquake measured at the KJMA station site which has a peak ground acceleration of 0.82g, as shown in Figure 5. It should be noted that the entire analyses are performed in time duration of 10 sec including PGA in whole strong duration.

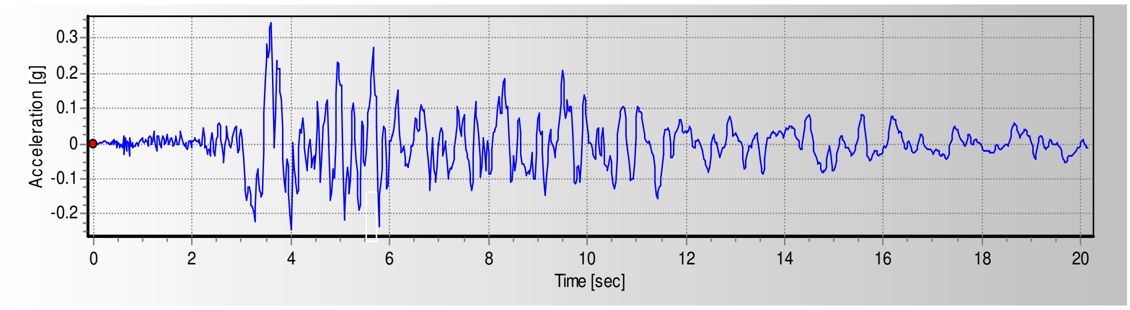

FIG. 4. Northridge Earthquake (1994) Measured at the Arleta Station Site

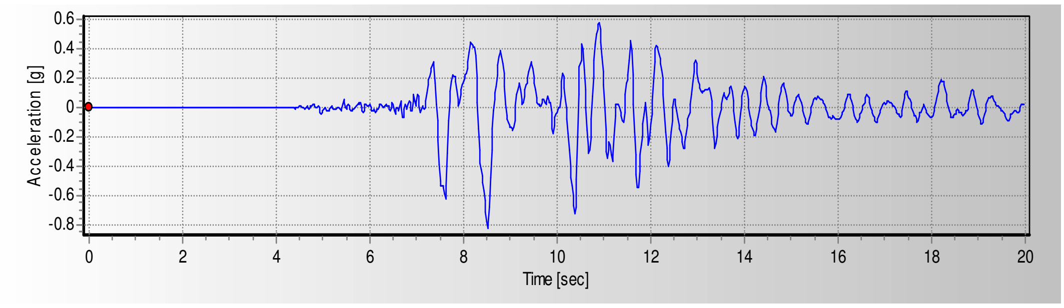

FIG. 5. Kobe Earthquake (1995) Measured at the KJMA Station Site

6. UNANCHORED AND ANCHORED TANKS

Uplifting phenomenon separates unanchored and anchored tanks behavior when they subject earthquake. This phenomenon causes to produce main compressive stresses in unanchored tanks wall. Of course two kinds of compressive stress appear in tanks wall, the one is axial compressive stresses and the other is hoop compressive stresses. Tables 1 and 2 show considerable increase of hoop compressive stress in unanchored tanks than anchored tanks, but because of influence of soil flexibility on axial compressive stresses, variations of these stresses don't depend on anchorage conditions, since sometimes axial compressive stresses in anchored tanks is much higher than unanchored tanks and vice versa.

Table 1- Maximum Responses of Anchored and Unanchored Tanks under Northridge Earthquake

H/D Ratio	Maximum Hoop Compressive Stress (Mpa)- Unanchored Tank	Maximum Hoop Compressive Stress (Mpa)- Anchored Tank	Maximum Axial Compressive Stress (Mpa)- Unanchored Tank	Maximum Axial Compressive Stress (Mpa)- Anchored Tank	Base Plate Uplifting (m)
0.33	-16.24	-12.83	-18.73	-7.30	0.005
0.75	-72.00	-7.10	-56.40	-15.80	0.044
1.50	-169.30	-9.07	-65.12	-31.30	0.125

Table 2- Maximum Responses of Anchored and Unanchored Tanks under Kobe Earthquake

H/D Ratio	Maximum Hoop Compressive Stress (Mpa)- Unanchored Tank	Maximum Hoop Compressive Stress (Mpa)- Anchored Tank	Maximum Axial Compressive Stress (Mpa)- Unanchored Tank	Maximum Axial Compressive Stress (Mpa)- Anchored Tank	Base Plate Uplifting (m)
0.33	-82.60	-29.30	-50.52	-11.75	0.042
0.75	-260.90	-14.38	-58.30	-32.40	0.449
1.50	-331.80	-14.16	-63.70	-42.67	0.474

As the results verify in second column of Table 2, both the medium and tall tanks would experience stress more than yield stress under Kobe Earthquake if they were not anchored at the base.

7. VERTICAL DISPLACEMENT OF LIQUID SURFACE (SLOSHING)

The other phenomenon that is created in tanks is sloshing. This phenomenon should take into consideration for estimation of free board requirement as well as convective component effect. Vertical displacement of liquid surface due to free-surface sloshing given by code guidelines and regulations is quite different with amounts obtained from finite element analysis and observed facts in previous earthquakes. Time history responses of sloshing display effect of anchorage condition at the base of tanks, as observed in Figures 6 to 8.

As these figures indicate, all tanks with different aspect ratios reach 20 cm or less sloshing amplitude under Northridge-type earthquake. On the contrary, anchorage condition affects much significantly the seismic performance of tanks under Kobe-type earthquake. As a result, unanchored tank with the highest aspect ratio gets 200 cm sloshing amplitude under Kobe earthquake. It is very interesting to observe almost similar sloshing level at all anchored tanks under each earthquake motion.

8. CONCLUDING REMARKS

1- Main difference between unanchored and anchored tanks is relevant to uplifting phenomenon. This phenomenon produces axial compressive stress and hoop compressive stress in tanks wall that hoop compressive stress is more sensitive to anchorage conditions, whereas axial compressive stress is more sensitive to flexibility of soil.

2- Tall and Medium tanks are more sensitive to anchorage conditions than broad tank under strong shaking like Kobe earthquake, but only tall tank is more sensitive to anchorage conditions than two other tanks under earthquake with lower PGA like Northridge earthquake at Arleta Station.

3- Uplifting in Tall tank base plate is much larger than the others. It should be noted that in tall and medium tanks, the amounts of uplifting are almost similar under strong earthquake like Kobe earthquake.

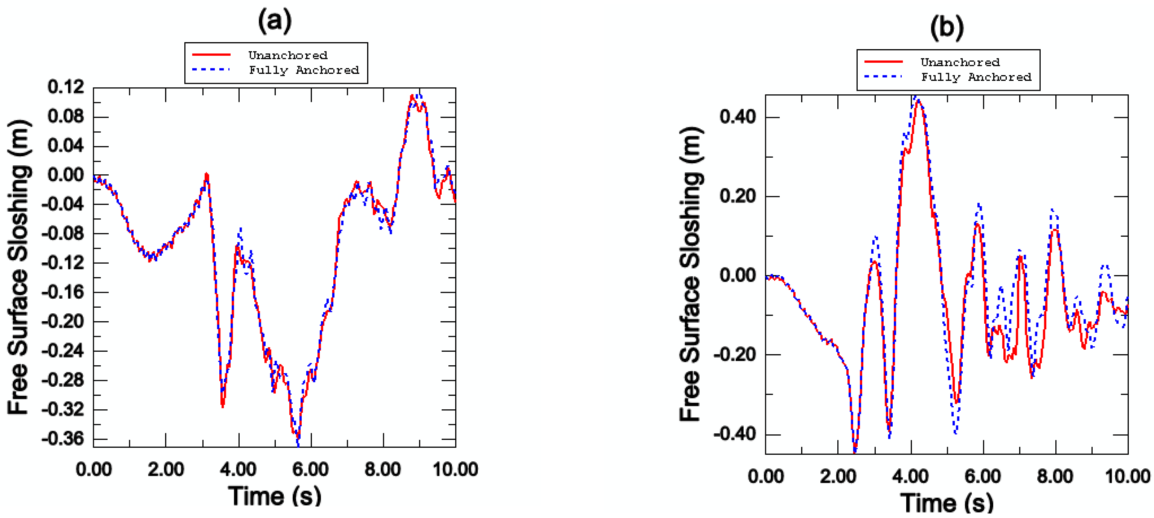

FIG.6. Typical Vertical Displacement Time History for Fluid Free Surface in Broad Tank under (a)Northridge and (b)Kobe Earthquakes.

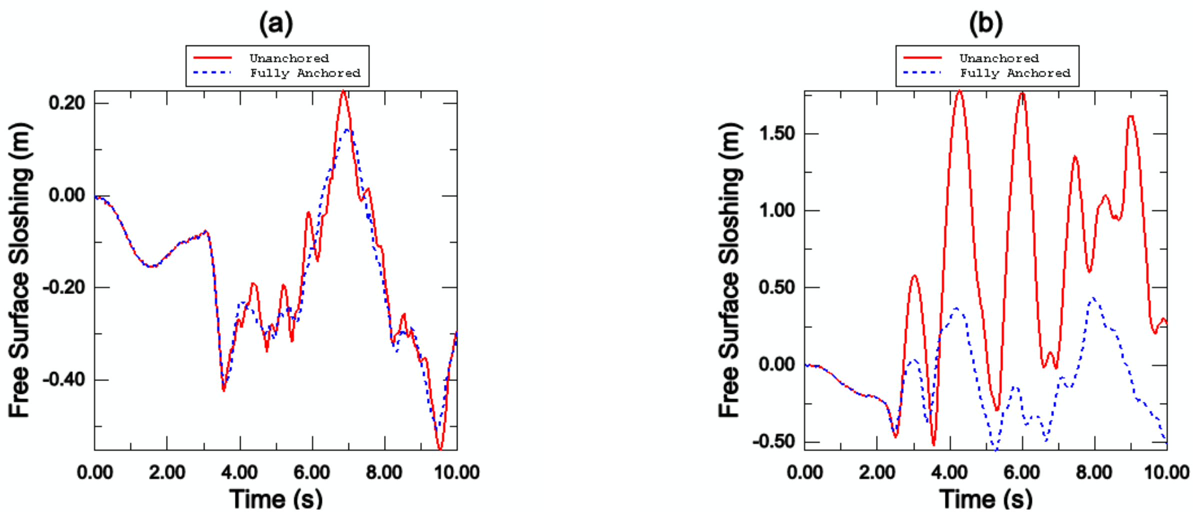

FIG.7. Typical Vertical Displacement Time History for Fluid Free Surface in Medium Tank under (a)Northridge and (b)Kobe Earthquakes

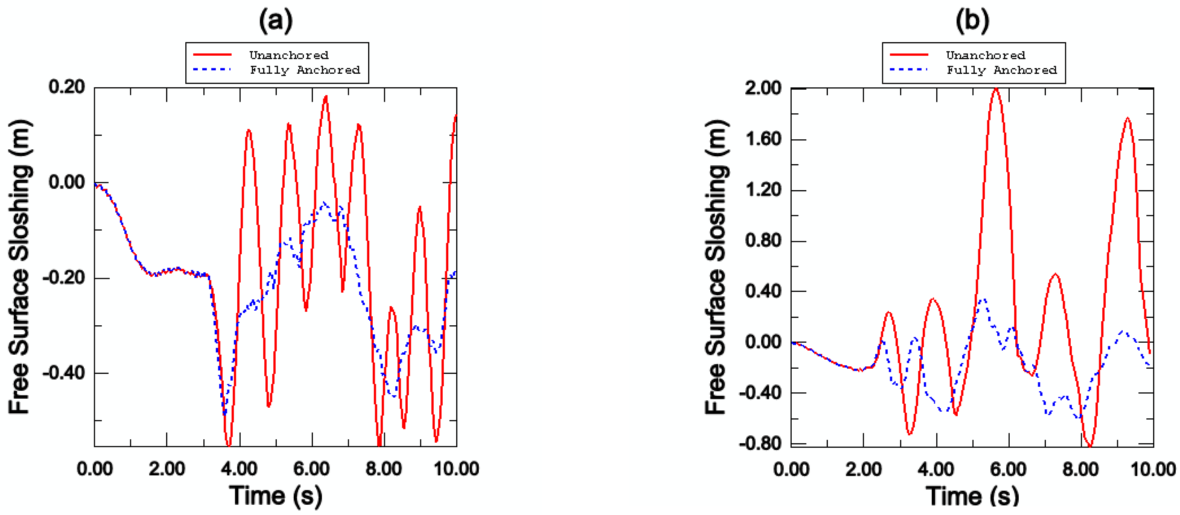

FIG.8. Typical Vertical Displacement Time History for Fluid Free Surface in Tall Tank under (a)Northridge and (b)Kobe Earthquakes

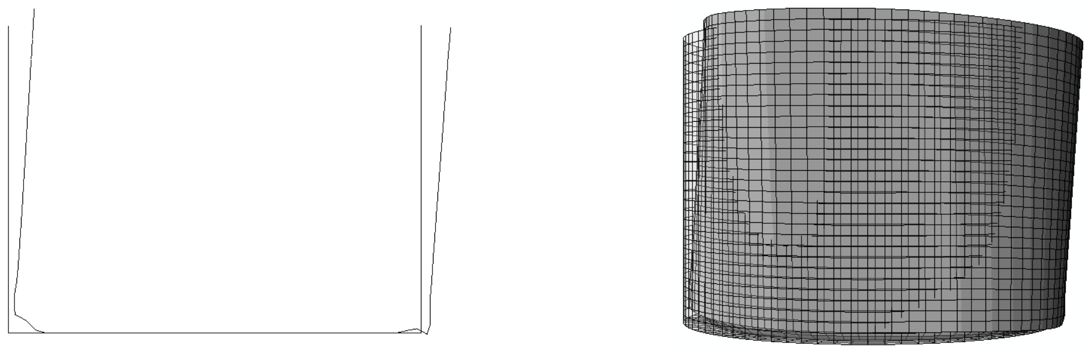

FIG.9. Typical two-dimensional and three dimensional deformation of tank under earthquake

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