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FACTORS AFFECTING THE NONLINEAR SEISMIC RESPONSE OF UNANCHORED TANKS

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ABSTRACT

The present study investigates the effects of liquid hydrodynamic pressures exerted on thin-walled unanchored liquid storage tanks during earthquake motions. Several complexities are involved in the analysis of such tanks due to successive contact and separation between base plates and foundations, large amplitude deformations of base plates, material yielding, soil-tank interaction, and large-amplitude free surface sloshing. Thus, simplified methods in the analysis of unanchored tanks are inadequate to capture the complex seismic response of these structures. A finite element program capable of handling the complexities associated with the nonlinear transient response of unanchored tanks was developed and used to assess the effects of the aforementioned factors on the nonlinear time-dependent seismic response of unanchored tanks.

Keywords: Unanchored Tanks, Liquid-Structure Interaction, Nonlinear Seismic Response, Hydrodynamic Response

INTRODUCTION

Liquid storage tanks are important components of lifeline and industrial facilities. They are critical elements in municipal water supply and fire fighting systems, and in many industrial facilities for storage of water, oil, chemicals and liquefied natural gas. Behavior of large tanks during seismic events has implications far beyond the mere economic value of the tanks and their contents. If, for instance, a water tank collapses, as occurred during the 1933 Long Beach and the 1971 San Fernando earthquakes, loss of public water supply can have serious consequences. Similarly, failure of tanks storing combustible materials, as occurred during the 1964 Niigata, Japan and the 1964 Alaska earthquakes, can lead to extensive uncontrolled fires.

A number of studies were reported in the literature on investigations of the seismic behavior of unanchored tanks. Due to the complexity of the problem, most of the original studies were experimental in nature. Several simplified theoretical investigations were also conducted and a few of these studies have been used as a basis for current design standards. Yet, the large-scale damage to unanchored tanks in recent earthquakes highlighted the need for a careful analysis of such tanks.

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Numerical discretization approaches, using the finite element or the finite difference methods, have been employed recently to analyze unanchored tanks. However, assumptions of varied degrees of approximations were made to simplify the analysis, such as the substitution of the base plate by "equivalent" springs, the performing of a pseudo-dynamic analysis in lieu of the full dynamic analysis, the linearization of a portion of the problem such as considering the tank wall to be rigid or ignoring liquid sloshing, and the use of approximate analytical expressions for the hydrodynamic pressures to eliminate the liquid degrees of freedom.

The present study employs the finite element technique to analyze unanchored tanks taking into consideration base plate contact with a flexible foundation and its large-amplitude deformations, buckling behavior of the shell, material yielding and large-amplitude free-surface sloshing. A three-dimensional fully coupled liquid-structure model was subjected to a seismic ground motion and the time history response of various design parameters were obtained.

DESCRIPTION OF THE NUMERICAL SIMULATION

The finite element program DYNAZ, which is capable of simulating the complex transient behavior of unanchored liquid storage tanks, when subjected to strong seismic base excitations, was developed (El-Zeiny, 1995). The program takes into consideration large amplitude liquid sloshing and the geometric, material and contact nonlinearities of the tank shell and base plate. The computer simulation included the following features:

- A variational principle that forms the basis for the numerical discretization of fully-coupled nonlinear liquid-structure interaction problems with free surface sloshing. The program uses an updated Eulerian-Lagrangian description of the liquid-structure interface in order to enforce compatibility between structure and liquid elements.
- An up-to-date finite element technology in the analysis of structures and curved shells using the degeneration concept, and considering both material plasticity and geometric nonlinearly.
- Free surface sloshing modeling that utilizes the nonlinear wave theory formulation. The updated Lagrangian description of the liquid domain boundaries is utilized to keep track of the free surface position at any time.
- The foundation is modeled using tensionless springs. This approach was found to be efficient in representing the nonlinear uplift problem.
- An efficient handling of the contact/uplift analysis of unanchored tanks. A Lagrange multiplier technique was employed to enforce both displacement compatibility and force transmissibility constraints along the unknown contact surface.
- The nonlinear governing equations are solved using an efficient time integration technique that has been developed specifically to solve liquid-structure interaction problems.

NUMERICAL IMPLEMENTATION

DYNAZ was used to calculate the earthquake response of two liquid storage tanks of different aspect ratios: a broad tank and a tall tank. The broad tank is 40 ft high and has a radius of 60 ft and the tall tank is 72 ft of high, 24 ft in radius. Both the tank and the contained liquid were discritized as shown in Figures (1) and (2). Both tanks has a shell and base thickness of 1 inch and assumed full of water to capacity. Each of the two tanks were subjected to two different earthquake motions: the East-West component of the 1940 El-Centro earthquake which has a peak ground acceleration of 0.214 g, as shown in Figure (3), and the record from the Northridge earthquake measured at the Arleta site which has a peak ground acceleration of 0.344 g, as shown in Figure (4), and measured in a direction of 90° from the hypocenter direction. The base plates of both tanks were considered supported on a tensionless elastic foundation of a uniform stiffness of 1000 lb/in/in^2 in compression. Table (1) shows the maximum response of unanchored tanks using the small deflection theory.

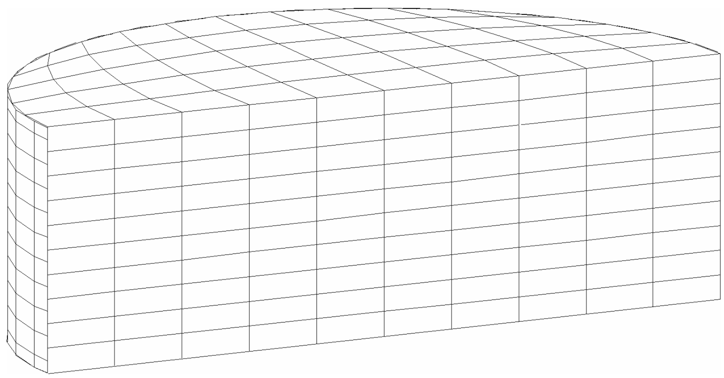

FIG. 1. Finite Element Mesh for the Coupled Liquid-Broad Tank System

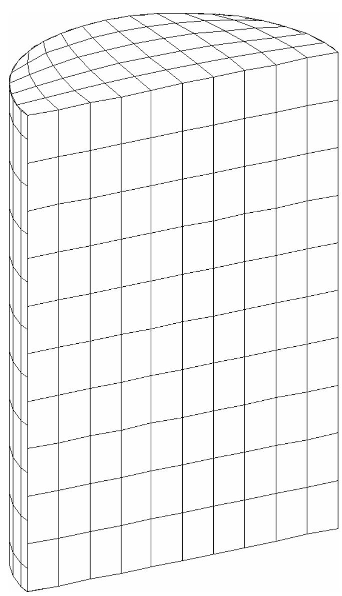

FIG. 2. Finite Element Mesh for the Coupled Liquid-Tall Tank System

It was observed that the response of the unanchored tank was governed primarily by a rocking motion. By observing the Fourier spectrum of this motion, it was found that the rocking motion has a dominant period of 0.41 sec for the broad tank and 0.82 sec for the tall tank. Based on these periods, the foundation rocking damping is estimated to be 5%.

TABLE 1. Response in the Case of Small Deflection Assumption

Response Parameter	El-Centro Record		Northridge Record	
	Broad	Tall	Broad	Tall
Top Lateral Acceleration	1.999 g	0.934 g	2.001 g	0.845 g
Top Lateral Deflection (in)	7.43	5.66	6.24	13.49
Total OTM / WR	0.200	0.380	0.198	0.477
Wall OTM / WR	0.075	0.317	0.065	0.353
Base Shear / W	0.292	0.243	0.258	0.293
Base Axial Stress (Ksi)	-4.75	-6.71	-4.62	-7.90
Base Hoop Stress (Ksi)	9.56	8.46	10.84	8.07
Axial Stress at 0.25H (Ksi)	-2.47	-4.69	-2.04	-5.58
Hoop Stress at 0.25H (Ksi)	19.85	11.51	21.50	12.89
Maximum Uplift Displacement (in)	1.05	1.75	1.50	2.87
Minimum Contact Area	0.732	0.671	0.733	0.610

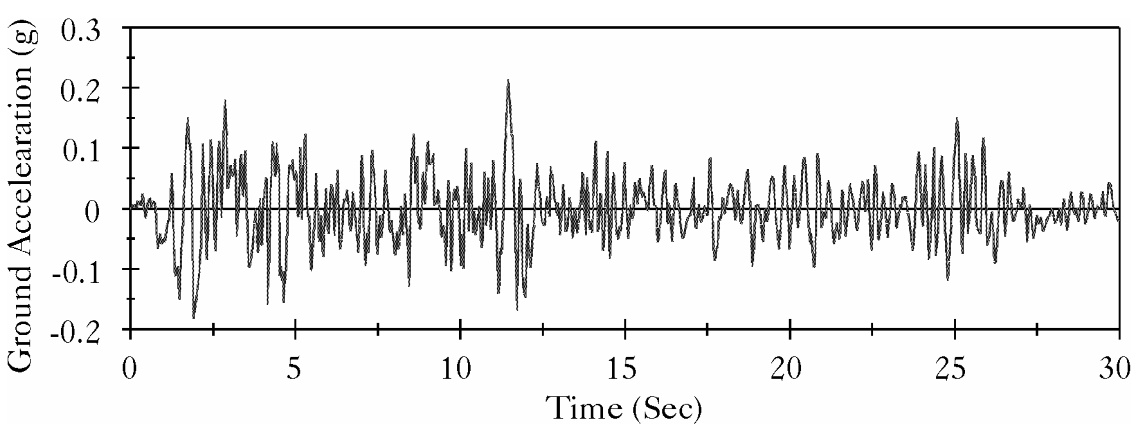

FIG. 3. East West Component of the 1940 El-Centro Earthquake

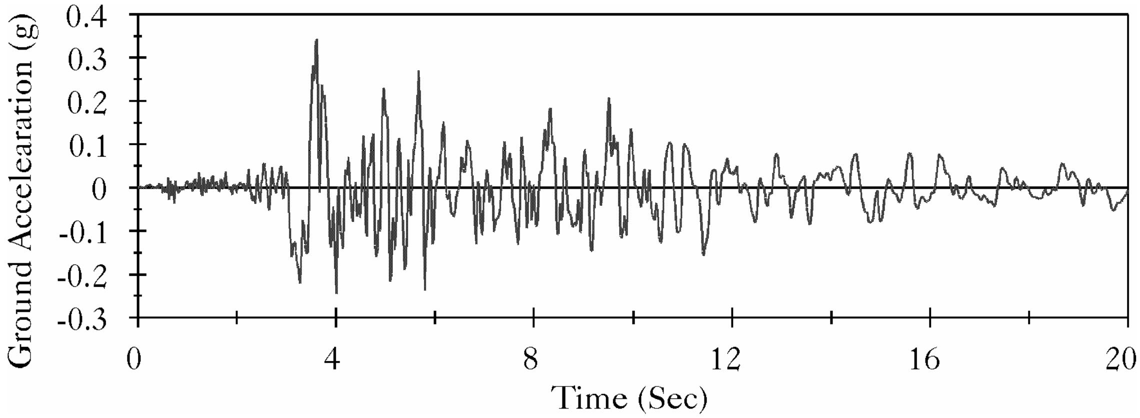

FIG. 4. Northridge Earthquake Measured at Arleta Site

EFFECT OF FOUNDATION STIFFNESS

In order to evaluate the effect of the stiffness of the supporting foundation on the dynamic response of unanchored tanks, the tank base plate was considered supported on a tensionless elastic foundation of a uniform stiffness of 100 lb/in/in^2 in compression. Table (2) shows the maximum response of unanchored tanks using the small deflection theory.

TABLE 2. Response in the Case of Tanks on Softer Foundation

Response Parameter	El-Centro Record		Northridge Record	
	Broad	Tall	Broad	Tall
Top Lateral Acceleration	0.851 g	0.504 g	0.831 g	0.824 g
Top Lateral Deflection (in)	10.16	5.91	6.03	15.01
Total OTM / WR	0.161	0.228	0.200	0.277
Wall OTM / WR	0.057	0.191	0.057	0.245
Base Shear / W	0.224	0.144	0.227	0.220
Base Axial Stress (Ksi)	-2.41	-4.52	-1.92	-4.50
Base Hoop Stress (Ksi)	8.11	5.39	7.95	7.40
Axial Stress at 0.25H (Ksi)	-1.01	-3.55	-0.72	-3.63
Hoop Stress at 0.25H (Ksi)	18.72	10.53	19.76	12.22
Maximum Uplift Displacement (in)	1.58	1.74	1.90	3.60
Minimum Contact Area	0.817	0.768	0.817	0.732

The dominant period of the rocking mode of the tall tank increased to 1.16 sec while the one for the broad tank showed almost no change. This is attributed to the fact that the portion of the base plate of the broad tank located in the middle of the tank remains inactive in a horizontal position during the earthquake. The portion near the edges is frequently penetrating into the foundation and uplifting above it. Because of high foundation stiffness, the penetration displacement is small as compared to the uplift displacement. As a result, the resistance of the base plate to the uplifting force becomes the governing factor in the rocking motion of the tank. On the other hand, most of the base plate of the tall tank showed rocking motion. Thus, the period of the tank increased due to the decrease in the rotational stiffness of the base plate. This result in hydrodynamic forces, which are lower than those exerted when the tank was supported on a stiffer foundation.

In addition, increasing the foundation flexibility caused the contact zone to be larger and pressure distribution on the foundation was more uniform than those of stiffer foundations. As a result, the compressive stresses in the bottom of the tank shell were lower, because they were distributed more widely along the base of tank wall, and the uplift displacements were higher than those of tanks supported over more rigid foundations.

LARGE DEFLECTION EFFECT

The response of the two tanks was calculated using the large deflection assumption and the tank base plate was considered supported on a tensionless elastic foundation of a uniform stiffness of 1000 lb/in/in^2 in compression. Table (3) shows the maximum response of these tanks to El-Centro and Northridge earthquakes, respectively.

TABLE 3. Response in the Case of Large Deflection Assumption

Response Parameter	El-Centro Record		Northridge Record	
	Broad	Tall	Broad	Tall
Top Lateral Acceleration	1.345 g	0.812 g	1.652 g	0.853 g
Top Lateral Deflection (in)	1.65	6.65	1.30	8.90
Total OTM / WR	0.127	0.374	0.167	0.470
Wall OTM / WR	0.047	0.314	0.060	0.348
Base Shear / W	0.183	0.232	0.237	0.291
Base Axial Stress (Ksi)	-1.68	-6.55	-1.79	-6.50
Axial Stress at 0.25H (Ksi)	-0.93	-4.61	-0.81	-4.62
Hoop Stress at 0.25H (Ksi)	17.46	11.25	18.73	12.49
Maximum Uplift Displacement (in)	0.36	1.56	0.46	2.52
Minimum Contact Area	0.792	0.683	0.793	0.622

The table shows a reduction in the uplift displacements of the base plate and an increase in the contact area between the base plate and the foundation due to the membrane effect that increased the uplifting stiffness of the base plate. This also has caused the dominant period of the rocking motion to decrease to 0.21 sec for the broad tank and 0.55sec for the tall tank. In addition, the membrane effect of the tank shell has reduced the deflection and acceleration at top of the broad tank. As a result, the impulsive acceleration was less and the resulting hydrodynamic forces were also less. For a tall tank, which acts more like a cantilever, this did not have much effect on the tank shell acceleration and the hydrodynamic forces were not altered much.

Axial stresses at the bottom of the tank shell were less than those using the small deflection assumption. This is attributed to the reduction in the uplift displacements as well as the increase in the contact area of the tank base plate.

EFFECT OF PLASTICITY

The excessive uplifting displacement of the base plate of an unanchored liquid storage tank usually causes a plastic hinge to develop in the connection between the base plate and the shell. Table (4) shows the maximum response of the unanchored tanks to El-Centro and Northridge earthquakes, respectively, taking into consideration the possibility of the formation of this plastic hinge and the large deflection effect. The tank base plate was considered supported on a tensionless elastic foundation of a uniform stiffness of 1000 lb/in/in^2 in compression.

TABLE 4. Response in the Case of Large Deflection and Plasticity Assumptions

Response Parameter	El-Centro Record		Northridge Record	
	Broad	Tall	Broad	Tall
Top Lateral Acceleration	2.810 g	0.576 g	1.390 g	0.785 g
Top Lateral Deflection (in)	3.47	4.70	1.08	9.44
Total OTM / WR	0.118	0.305	0.154	0.394
Wall OTM / WR	0.039	0.260	0.055	0.312
Base Shear / W	0.148	0.185	0.218	0.254
Base Axial Stress (Ksi)	-2.75	-5.43	-1.86	-6.74
Axial Stress at 0.25H (Ksi)	-1.54	-3.66	-1.00	-4.45
Hoop Stress at 0.25H (Ksi)	17.20	8.19	18.02	8.56
Maximum Uplift Displacement (in)	1.22	1.73	0.52	3.13
Minimum Contact Area	0.732	0.720	0.768	0.659

The lateral stiffness of the unanchored tank shell may be divided into two components: a vertical stiffness and a horizontal stiffness. The vertical stiffness is caused by the cantilever effect, which depends mainly on the rotational stiffness provided from the connection between the base plate and the tank shell. The horizontal stiffness is caused by the hoop effect due to the horizontal curvature of the shell. The formation of the plastic hinge decreases the vertical stiffness of the tank shell leading to a longer period for its lateral vibration. As a result, the hydrodynamic forces on the tank wall are less than those exerted when the plasticity was ignored. In addition, formation of the plastic hinge increased the uplift displacements of the base plate and decreased the contact area of the base plate with the foundation.

EFFECT OF BASE PLATE THICKNESS

The uplift mechanism that governs the response of unanchored tanks is influenced by the thickness of the base plate. Tanks with thinner base plate uplift more and consequently more axial stresses are developed at the bottom of the tank shell. In addition, decreasing the thickness of the base plate reduces the rocking stiffness and consequently lengthens the rocking period. This causes the developed hydrodynamic forces to be slightly less than those of tanks with thicker base plate. Table (5) shows the maximum response of the unanchored tanks to El-Centro and Northridge earthquakes, respectively, assuming that the base plate thickness is 0.5 inch and considering the large deflection effect.

TABLE 5. Response in the Case of Reduced Base Plate Thickness and Large Deflection Assumption

Response Parameter	El-Centro Record		Northridge Record	
	Broad	Tall	Broad	Tall
Top Lateral Acceleration	1.22g	0.78 g	2.09 g	0.80 g
Top Lateral Deflection (in)	1.75	6.46	1.89	9.9
Total OTM / WR	0.104	0.358	0.156	0.430
Wall OTM / WR	0.039	0.304	0.055	0.345
Base Shear / W	0.147	0.220	0.214	0.288
Base Axial Stress (Ksi)	-1.64	-7.03	-2.36	-7.40
Axial Stress at 0.25H (Ksi)	-0.76	-5.15	-1.36	-5.40
Hoop Stress at 0.25H (Ksi)	16.39	10.82	17.71	11.60
Maximum Uplift Displacement (in)	0.46	1.71	0.727	2.96
Minimum Contact Area	0.768	0.646	0.756	0.622

CONCLUSION

A finite element program was developed to analyze the complexities associated with the nonlinear dynamic response of unanchored liquid storage tanks. It was observed that the response of unanchored tanks was dominated by the uplift mechanism that varied nonlinearly with the intensity and frequency of the input motion. The coupling of the uplift mechanism with out-of-round distortions resulted in high compressive axial membrane stresses developed over a narrow contact zone. This effect is reflected by the sharp peaks on the compression side of the time histories of axial stresses, which occurred simultaneously with large uplifting displacements.

Many factors that affect the seismic response of unanchored tanks were investigated. It was found that unanchored tanks supported on flexible foundations exhibit lower compressive stresses and higher uplift displacements than those supported over more rigid foundations. This was attributed to flexible foundations, where the contact zone is larger and the pressure distribution on the soil is more uniform than those of rigid foundations. In addition, foundation softness lengthens the rocking period of the tank resulting in less hydrodynamic forces. Membrane forces induced due to large deflections were found to reduce uplift displacements and consequently axial stresses. Formations of a plastic hinge in the connection between the tank shell and base plate increase uplift displacements. Reducing the thickness of the base plate causes the tank to uplift more and consequently more axial stresses are developed at the bottom of the tank shell. In addition, decreasing the base plate thickness reduces the rocking stiffness and consequently lengthens the rocking period, and consequently, the developed hydrodynamic forces were less than those for tanks with thicker base plates.

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APPENDIX I. NOTATION

The following symbols were used:

g	= acceleration of gravity
H	= tank height
R	= tank radius
OTM	= overturning moment
W	= tank weight