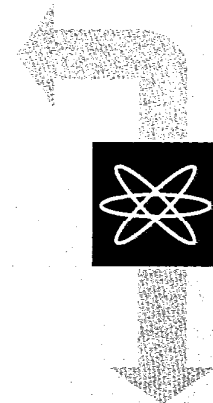


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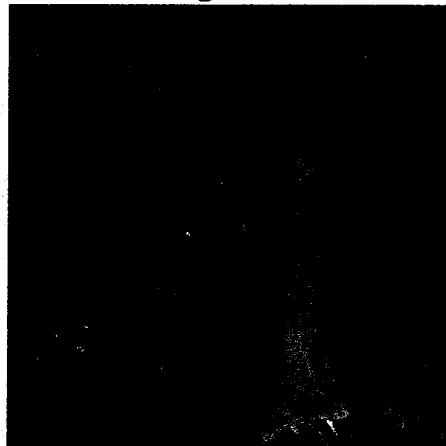
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# Simulation of Dynamic Behavior of Unanchored Tanks

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**ABSTRACT:** Evaluation of the commonly used seismic design procedures for unanchored liquid storage tanks has shown that current standards are inconsistent in predicting the behavior of these structures. In general, the estimation of liquid-exerted overturning moments lacks explicit consideration of the support effects. The overturning moment caused by the hydrodynamic pressure tends to lift the shell off its foundation which may cause buckling of the shell on one side and a separation of the base plate from the shell on the other, thereby releasing the tank contents. A finite element program capable of handling the complexities associated with the nonlinear dynamic response of unanchored tanks was developed. It was observed that the overturning moment exerted on an unanchored tank may be smaller than that exerted on a similar anchored tank, yet the stresses at the shell bottom of an unanchored tank shell are generally much larger than those of an anchored tank subjected to the same ground motion.

## 1 INTRODUCTION

The present study was carried out to investigate the effects of transient liquid-exerted hydrodynamic pressures on thin-walled unanchored liquid storage tanks during earthquake motions. Complexities arise due to the successive contact and separation between the base plate and its foundation, nonlinear fluid-structure interaction, large-amplitude deformations of the base plate, pre- and post-buckling behavior of the shell, material yielding, soil-tank interaction, and large-amplitude free-surface sloshing.

Numerous studies were performed to investigate the seismic behavior of unanchored tanks. Due to the complexity of the problem, most of the original studies were experimental in nature. In addition, several simplified theoretical investigations were conducted. 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.

Numerical discretization approaches using the finite element method or the finite difference method 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 was obtained. In addition, a comparison between the earthquake response of anchored and unanchored tanks is presented.

## 2 FUNDAMENTAL APPROACH

A computer model capable of simulating the complex transient behavior of unanchored liquid storage tanks, when subjected to strong seismic base excitations, was developed. The model 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 nonlinearity.
- Potential flow modeling through the usage of an Eulerian formulation.
- 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 and adequate 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 comparability 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.

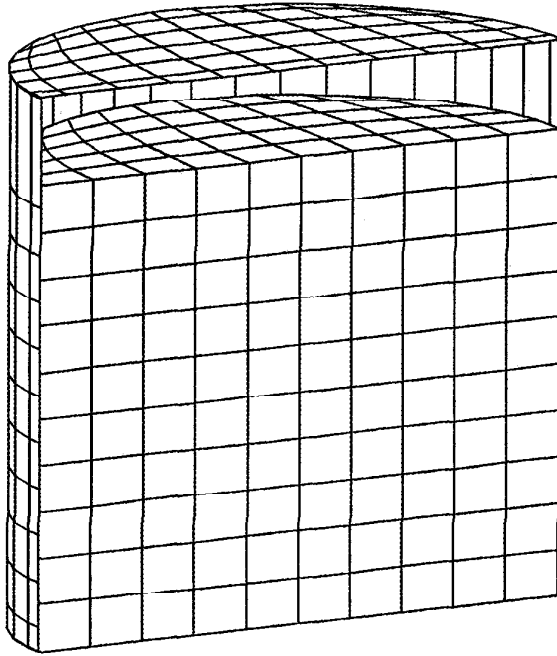


Figure 1: Finite element mesh of the coupled liquid-tank system

### 3 NUMERICAL IMPLEMENTATION

The preceding basic approach was incorporated in a nonlinear transient finite element program DYNAZ ( Zeiny , 1995 ). The program was used to analyze an unanchored tank located at the American National Can site which, during the 1994 Northridge earthquake, experienced severe ground motion (Haroun, 1995). The tank suffered elephant foot buckling at the bottom of the shell. It apparently uplifted during the earthquake severing the adjacent piping and releasing its contents. The tank is 37 ft in diameter, 32 ft in height and has a shell of 3/8 in thickness. It is supported on a concrete pad and was filled with water to a depth of 28.3 ft at the time of the earthquake. The tank was subjected to the record measured at the Arleta site which has a peak ground acceleration of 0.344g.

As shown in Fig. (1), the liquid inside the tank was discretized to 500 fluid elements with a total of 726 nodes. The tank was discretized to 359 isoparametric shell elements with a total of 428 nodes. The finite element formulation simulated both the fluid-structure interaction and the free surface sloshing, and large-deflection theory was used to account for buckling. Two different boundary conditions for the tank were considered: anchored tank condition in which the tank base plate is considered fully fixed to a rigid foundation, and the unanchored tank condition in which the tank base plate is considered supported on a tensionless elastic foundation of a uniform stiffness of 100 lb/in/in<sup>2</sup> in compression. Table (1) shows a comparison between the tank responses under the anchored and unanchored conditions. Note that  $W$  denotes the total weight of the contained liquid,  $R$  is the tank radius and  $g$  is the acceleration of gravity.

The response of the unanchored tank was governed primarily by a rocking motion. This mode was found to have a dominant period of 0.4 sec. and, based on this

Parameter	Anchored	Unanchored
Total Overturning Moment	0.407 WR	0.320 WR
Liquid Overturning Moment	0.383 WR	0.245 WR
Overturning Moment on Wall	0.303 WR	0.170 WR
Total Base Shear	0.473 W	0.276 W
Base Shear due to Liquid	0.454 W	0.257 W
Maximum Shell Acceleration	0.88 g	1.96 g
Maximum Uplift Displacement	-	1.22 in (3.10 cm)
Minimum Contact Area	-	73.2%
Axial Stress at Shell Bottom	-2.19 ksi (15.1 MPa)	-5.27 ksi (36.3 MPa)
Hoop Stress at Shell Bottom	1.45 ksi (10.0 MPa)	11.61 ksi (80.1 MPa)
Axial Stress at Shell Mid-height	-0.54 ksi (3.7 MPa)	-1.00 ksi (6.9 MPa)
Hoop Stress at Shell Mid-height	5.83 ksi (40.2 MPa)	5.42 ksi (37.4 MPa)

Table 1: Comparison Between Anchored and Unanchored Tank Responses

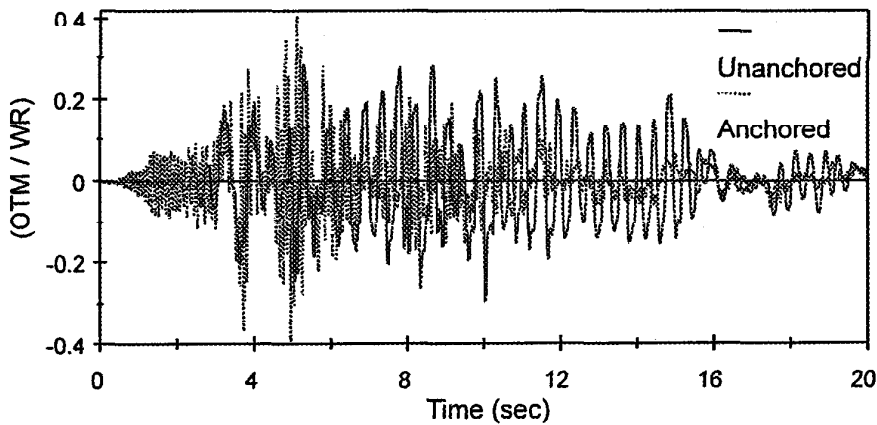


Figure 2: Overturning moment about the center of base of the ANC tank

period, the foundation rocking damping is estimated to be 3%. On the other hand, the response of the anchored tank was governed primarily by the flexible-impulsive pressure component which has a fundamental period of 0.09 sec. A Raleigh damping coefficient which provides 3% damping to the first mode and increasing values for the higher modes was chosen for the flexible-impulsive component. Since the rocking period is relatively large as compared to the flexible-impulsive period, the overturning moment exerted on the anchored tank was found to be larger than that exerted on the unanchored tank. However, due to the nature of the boundary conditions associated with the base of the unanchored tank, the axial and hoop stresses at the bottom of the unanchored tank shell were much larger than those of the anchored tank. Figures (2) and (3) show a time history comparison between the anchored and the unanchored tank for the normalized total overturning moment (OTM) measured at the center of the base plate and for the base axial stresses, respectively.

The contact characteristics of the unanchored tank with its foundation are important factors in evaluating the response of such a tank. Figure (4) shows the uplift displacement of the two extreme opposite points on the principal diameter which

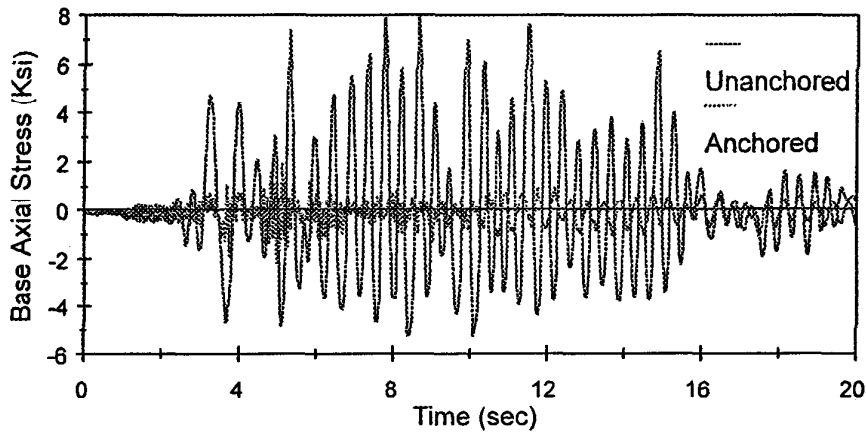


Figure 3: Base axial stress in the ANC tank shell

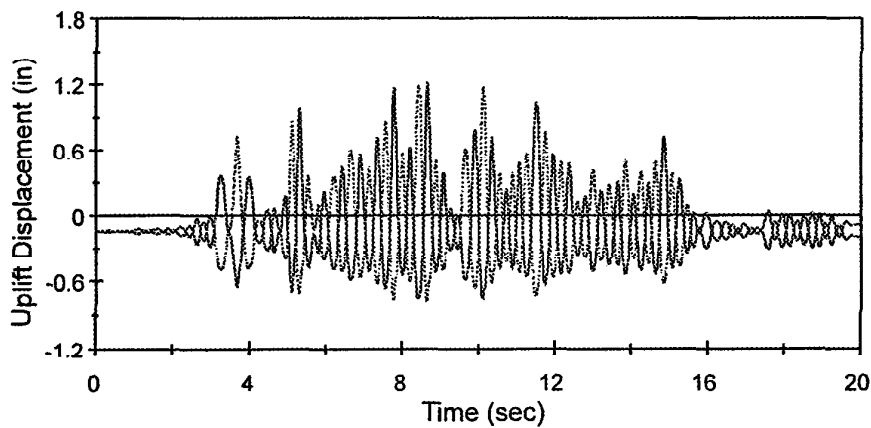


Figure 4: Uplift displacement of the two corner points on the principal diameter

parallels the earthquake excitation. It shows that the uplift displacement on the tension side is much higher than the penetration displacement on the compression side. Such a behavior is expected due to the tensionless nature of the foundation. In addition, Fig. (5) shows the time history of the change in the area of contact of the base plate with the foundation as compared to the total area. It should be noted that the results presented here include the effects of contact and geometric nonlinearities. The effect of material nonlinearities, considered by the formation of plastic hinges, increases the uplift displacement (El-Zeiny, 1995). Similar observations were noted for other unanchored tanks under different earthquake excitations.

#### 4 CONCLUSION

A finite element program capable of analyzing the complexities associated with the nonlinear dynamic response of unanchored liquid storage tanks was developed. It was observed that the overturning moment exerted on an unanchored tank may be smaller than that exerted on a similar anchored tank due to the longer-period nature of the rocking-motion which dominates the behavior of unanchored tanks. However,

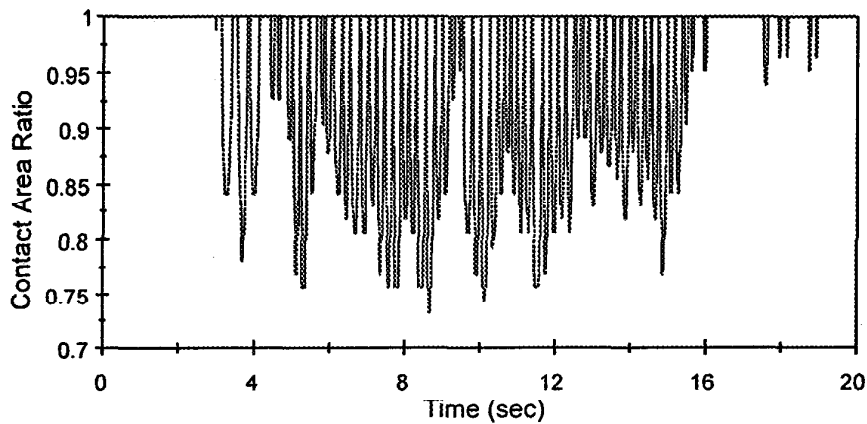


Figure 5: Percentage of bottom plate area in contact with the foundation

due to the nature of the boundaries associated with unanchored tanks at their base, the axial and hoop stresses at the bottom of an unanchored tank shell may be much larger than those of an anchored tank subjected to the same ground motion.

#### ACKNOWLEDGEMENTS

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