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A Computational Technique for the Nonlinear Dynamic Analysis of Unanchored Liquid Storage Tanks

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ABSTRACT

Methods used for predicting the seismic behavior of unanchored liquid storage tanks are often based on either a static or a pseudo-dynamic analysis in lieu of the full dynamic analysis. A finite element program capable of handling the complexities associated with the nonlinear transient response of unanchored tanks was developed. Among considered factors are the successive contact and separation between the base plate and the foundation, the nonlinear fluid-structure interaction, large-amplitude deformation of the base plate, material yielding, soil-tank interaction, and large-amplitude free-surface sloshing. It was observed that overturning moments exerted on unanchored tanks may be smaller than those exerted on similar anchored tanks, yet stresses at the bottom of an unanchored tank shell are generally much larger than those of an anchored tank subjected to same ground motion.

INTRODUCTION

Hydrodynamic pressures developed in unanchored tanks tend 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. Commonly used seismic analysis methods for these structures have shown repeatedly inconsistencies in predicting their actual behavior. Early investigations were either experimental in nature or based on simplified theoretical concepts, and these formed a basis for current design standards. Large-scale damage to unanchored tanks in recent earthquakes continued to highlight 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

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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. In the present study, a fully-coupled three-dimensional liquid-structure model is subjected to a transient seismic ground motion, and the time history response of various design parameters is obtained.

BASIC APPROACH

A computer model capable of simulating the complex transient behavior of unanchored tanks, when subjected to strong seismic base excitation, was developed. The model considers large amplitude liquid sloshing and the geometric, material and contact nonlinearities of the tank shell and base plate. The numerical discretization of the fully-coupled liquid-structure interaction problem was based on a variational principle. It used an updated Eulerian-Lagrangian description of the liquid-structure interface in order to enforce compatibility between structure and liquid elements. Curved shell elements developed by the degeneration concept with consideration of both material plasticity and geometric nonlinearity were used. Potential flow modeling of the liquid was achieved through the usage of an efficient Eulerian finite element. Free surface sloshing modeling was accomplished by a nonlinear wave theory formulation. An updated Lagrangian description of the liquid domain boundaries was utilized to keep track of the free surface position at any time. The foundation was modeled using tensionless springs. This approach was found to be efficient and adequate in representing the tank uplift. The handling of the contact/uplift phenomenon was achieved by employing a Lagrange multiplier technique to enforce both displacement compatibility and force transmissibility constraints along the unknown contact surface. Finally, the nonlinear governing equations were solved using an efficient time integration technique developed specifically to solve liquid-structure interaction problems.

UNANCHORED TANK RESPONSE

The preceding basic approach was incorporated in a nonlinear transient finite element program DYNAZ (Zeiny, 1995). It was utilized to estimate the earthquake response of two liquid storage tanks of different aspect ratios: a broad tank and a tall tank (Haroun, 1981). The broad tank is 40 ft high and has a radius (R) of 60 ft whereas the tall tank is 72 ft high and 24 ft in radius. Both tanks are assumed to have a uniform shell and base thickness of 1 inch, and to be full of water (weight W) to capacity. The tank base plate is considered supported on a tensionless elastic foundation of a uniform stiffness of 1000 $lb/in/in^2$ in compression. The response presented herein is for the ground motion record (Fig. 1) of the 1994 Northridge earthquake measured at the Arleta site. Figures (2) and (3) display the time history of the overturning moment at the center of the base plate, and the base axial stress of anchored and unanchored broad tanks whereas Figs. (4) and (5) show the same comparison for tall tanks. The response of the unanchored tank was governed primarily by a rocking motion. This mode

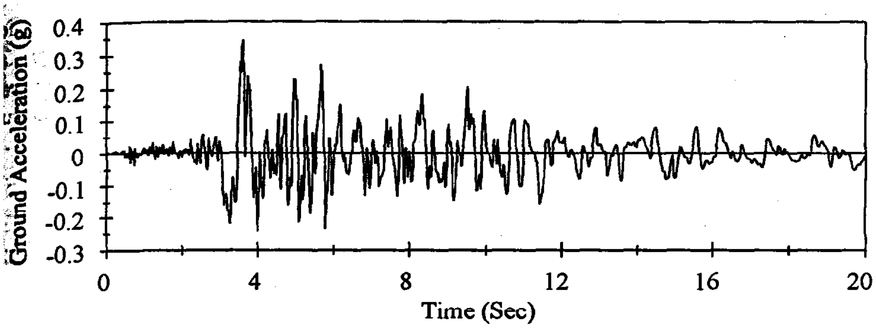

Figure 1: Northridge Earthquake Measured at Arleta Site

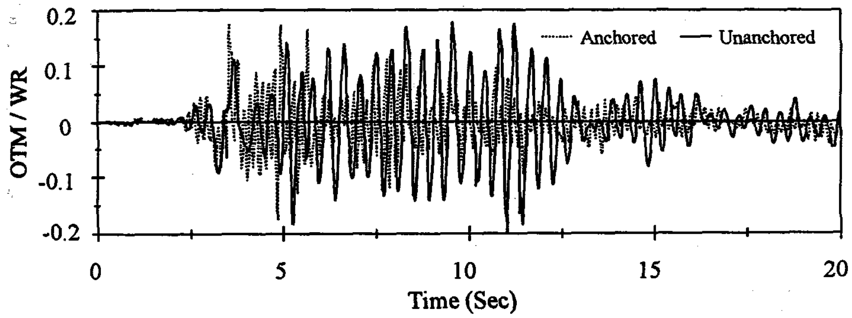

Figure 2: Overturning Moment at Center of Base of the Broad Tank

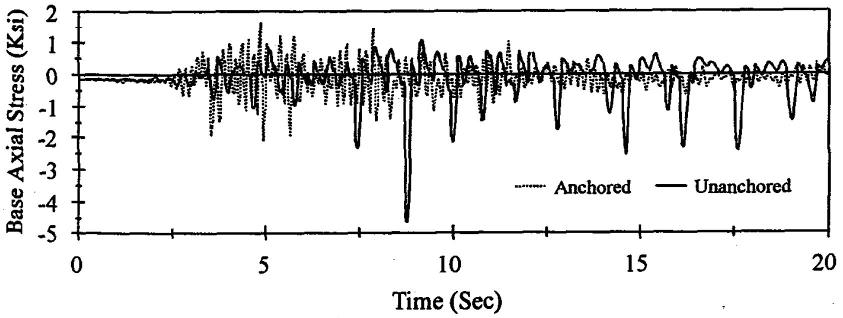

Figure 3: Base Axial Stress in the Broad Tank Shell

was found to have a dominant "period" of 0.41 sec for the broad tank and 0.82 sec for the tall tank. On the other hand, the response of the anchored tank was governed primarily by

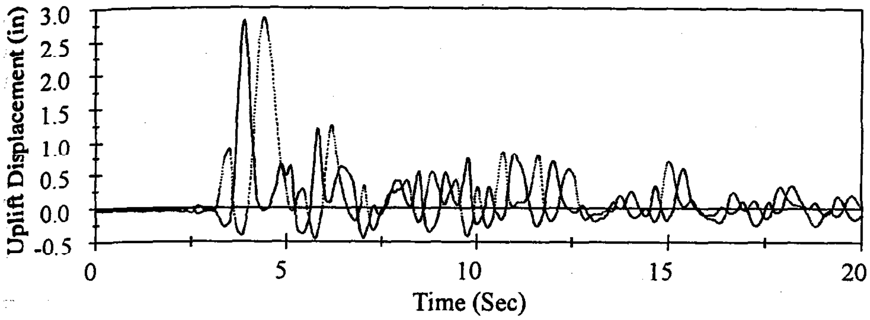

Figure 6: Uplift of End Points on Principal Diameter of the Tall Tank

PARAMETRIC STUDY

As the stiffness of the tensionless elastic foundation was reduced to 100 lb/in/in^2, the dominant period of the rocking mode of the tall tank increased to 1.16 sec while that for the broad tank showed almost no change. This is attributed to the observation that the middle portion of the base plate of the broad tank remained inactive in a horizontal position during the earthquake, as shown in Figure (7). On the other hand, most of the base plate of the tall tank showed rocking motion. In general, compressive stresses at the bottom of the tank shell were lower and the uplift displacements were higher, respectively, than those of tanks supported on stiffer foundations.

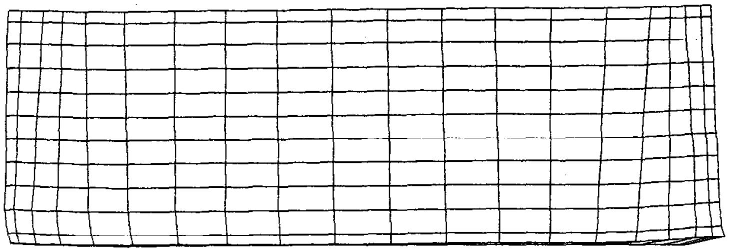

Figure 7: Deformed Shape of the Broad Tank

When large deflection theory of the base plate was adopted, the results showed a reduction in the uplift displacements of the base plate and an increase in the contact area of the base plate with the foundation. This also caused the dominant period of the rocking motion to decrease to 0.21 sec for the broad tank and 0.55 sec for the tall tank. Axial stresses at the bottom of the tank shell were generally less than those using the small deflection assumptions, although this reduction was much more pronounced for the broad tank.

Excessive uplifting displacement of the base plate causes plastic hinging to develop at the connection between the base plate and the shell. The lateral stiffness of an unanchored tank shell is contributed by the cantilever effect which depends, to a large extent, on the rotational stiffness of the connection between the base plate and the tank shell, and by the hoop effect due to the circumferential curvature of the shell. Thus, the formation of a plastic hinge decreases the shell stiffness leading to a longer period for its lateral vibration and to increased uplift displacements. As a result, the hydrodynamic forces on the tank wall are less than those exerted when the plasticity is ignored.

The uplift of unanchored tanks is also influenced by the thickness of the base plate. A tank with a thinner base plate uplifts more, and consequently, larger axial stresses are developed at the bottom of the tank shell. However, a decrease in the base plate thickness also lengthens the rocking period causing a slight reduction in the hydrodynamic forces than those on a tank with a thicker base plate.

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

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