Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VI)

10-4-7

SEISMIC BEHAVIOR OF UNANCHORED GROUND-BASED CYLINDRICAL TANKS

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SUMMARY

A review of the methods of seismic analysis of unanchored liquid storage tanks is presented along with an outline of an ongoing study to model the complex response mechanism of these structures. The study includes: 1. Nonlinear static and dynamic analyses of the tank's base plate under uplifting forces considering the nonlinear contact with the foundation and the underlying soil, the large deformation, and the inelastic response; 2. An analysis of the large-amplitude motion of the liquid and the corresponding hydrodynamic pressures; and 3. An analysis of the coupled response of the liquid, the shell and the base plate under moderate to severe earthquake motions.

INTRODUCTION

The dynamic behavior of unanchored tanks is totally different from anchored containers because the assumptions of symmetric and asymmetric behaviors of the tank shell are no longer valid due to the separation of the tank base from its foundation. The overturning moment caused by the hydrodynamic pressure tends to lift the shell off the foundation, and as the shell displaces upward, it pulls against the tank bottom causing the base plate to pick up liquid to resist the upward shell movement and to prevent further uplift. Accordingly, high compressive stress may develop in the shell causing its buckling.

PAST RESEARCH AND CURRENT PRACTICE

The methods for predicting the seismic response of ground-based anchored tanks under horizontal and vertical excitations are well established. However, there are no complete and truly reliable uplift analysis of unanchored tanks available in the literature. Past studies relevant to these tanks are divided to those dealing with the observation of damage and its correlation with empirical models, testing of tank models in a controlled environment, and theoretical studies, either analytical or numerical. Due to space limitations, the following review addresses only major published studies of unanchored tanks; additional details can be found in Ref. (2). Most pioneering studies were experimental in nature and performed on small scale models. In addition, simplified theoretical investigations focused attention on the behavior of the base plate which may dominate the tank's response. Strip plate idealizations have frequently been employed to develop formulas that can be applied directly in the design of these tanks.

Studies of Damage and Correlation with Empirical Models The Alaska earthquake of 1964 caused extensive damage to oil storage tanks, most of which were unanchored. Rinne (Ref. 19) developed a criterion for shell buckling due to lateral seismic forces by defining a shell buckling resistance coefficient. Hanson (Ref. 8) stated that the true stress and the precise progress of failure in uplifted tanks are hard to analyze, and that a reasonable estimate of the factor of safety against collapse is difficult to make. The validity of current design standards was assessed by comparing the observed damages during the 1979 Imperial Valley earthquake with predictions obtained from existing methods of analysis (Ref. 10), and it was concluded that current design standards may lead to a conservative design because of the very low allowable buckling stress. Based on a collection of damage data, a modification in the API 650 standard was suggested (Ref. 15) for better prediction of the seismic resistance. The analysis of damage during the 1983 Coalinga earthquake (Ref. 13) revealed that current U.S. practice underestimates the sloshing response in unanchored tanks covered by floating roofs, and does not adequately address the dynamic uplift mechanism and the buckling behavior.

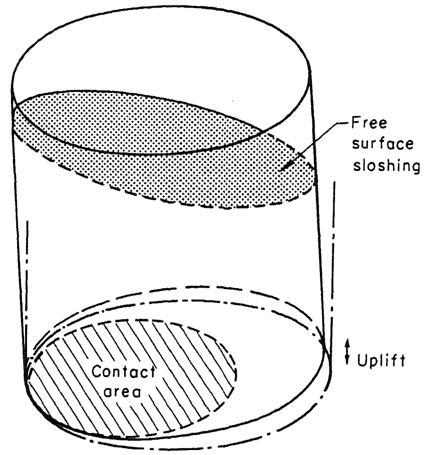

Fig. 1. Global seismic behavior of unanchored tanks.

Experimental Investigations The results of experimental studies on aluminum, broad and tall, cylindrical tank models subjected to earthquake-like base motions were summarized in Ref. (7). Due to tank wall flexibility, the impulsive hydrodynamic pressure component was amplified beyond the value expected in a rigid tank. Moreover, the uplift mechanism drastically altered the entire tank behavior, and there was a poor correlation between predicted and observed results, demonstrating the need for additional analytical studies. In a static tilt test (Ref. 6), it was noted that the tank tilted more and developed higher compressive stresses which were concentrated over a narrow contact zone. In Ref. (17), it was concluded that the critical buckling stress assumed in current standards for steel tank design might lead to rather conservative estimates of the buckling strength of a free base tank subjected to rocking motions. In addition, the uplifting stiffness of the base plate was considerably underestimated by ignoring the membrane stress. An experimental study (Ref. 4) concluded that the seismic response of tanks was significantly affected by the variation of the foundation flexibility, and a strong correlation was found between tank shell eccentricities, created by fabrication imperfections and/or shell deformations, and the out-of-round response. In Ref. (21), the buckling behavior of a small unanchored model constructed of Mylar A sheet with a floating roof was studied under horizontal base excitations. The buckling behavior of the model was in good agreement with the damage produced by the 1979 Imperial Valley earthquake, but the buckling predictions and tip over calculations using current standards were conservative by over a factor of two. Based on experimental evidence, an empirical design approach regarding tank-wall earthquake stability for unanchored tanks was proposed in Ref. (14). Since this approach was not based on a rigorous analytical model, it was recommended that a realistic analytical treatment of the nonlinear dynamic response mechanism of uplifting tanks should be developed. A static tilt test of a full scale tank model was presented in (Ref. 20), and a comparison with a theoretical analysis showed that the stress distibution around the shell-base corner and the contact condition between the base plate and the foundation must be carefully considered.

Theoretical Studies Clough (Ref. 5) proposed a simplified model for the uplifting of unanchored tanks but the load carrying capacity of the base plate was not taken into account. This model also neglects the deformation of the tank wall and the dynamic pressure on the base plate. Wozniak (Ref. 22) suggested a more realistic strip model which was later introduced in current standards. The model accounts for the flexural stiffness of the base plate using a small deflection theory but the flexibility of the tank wall and the foundation was not considered. Cambra (Ref. 4) modified this model by analyzing an empirical tie element model representing the tank base plate. It was found that both wall uplift and radial separation of tank base plate occurred at values larger than what design codes anticipated. The finite element technique is used (Ref. 1) to solve an axisymmetric uplift problem, and the tank was considered as a cylindrical shell resting on nonlinear springs with deflection-dependent stiffness. To determine the characteristics of these springs, the base plate was modeled as a strip resting on a rigid foundation and loaded by a uniformaly distributed pressure and an uplift force. In addition, two springs representing the bending and the extensional stiffnesses of the tank wall were introduced at the free end. A mechanical model having four degrees of freedom was suggested to analyze the dynamic rocking response of tanks with partial uplift of the bottom plate (Ref. 11). It was concluded in Ref. (12) that current codes can lead to significant underestimations of the maximum compressive stresses in the shell under condition of moderate shell uplift, and overestimations of the contribution of the fluid weight in resisting lift-off. Using a general purpose finite element computer code, a time history analysis of an unanchored tank was performed (Ref. 3). Gap conditions between the tank base and the supporting floor were specified to allow lift-off of the base but neither material nor geometric nonlinearities were considered. The results indicated that the stresses in the tank and the resultant loads on the floor of an unanchored tank were much greater than for a rigidly restrained tank. A simplified method of analysis, similar in concept to that of Ref. (1), was used to analyze unanchored tanks under static lateral loads (Ref. 18). The analysis of the cylindrical shell was performed based on a linear shell theory and it was assumed that both the base plate and the shell remain elastic and the foundation is rigid. It was concluded that the large membrane stresses developed in the bottom plate carry most of the load in the uplifted region. An analytical model for the response of an unanchored tank subjected to horizontal base excitation was developed (Ref. 16) by using Hamilton's principle. The uplift of the base plate was modeled as an rotational nonlinear spring whose characteristics were obtaind from previous static tilt tests, and it was assumed that the tank, which had a rigid foundation, rests on a flexible ground. It was concluded that significant unconservative estimates can be obtained if loads are calculated for an unanchored tank by assuming it to be anchored.

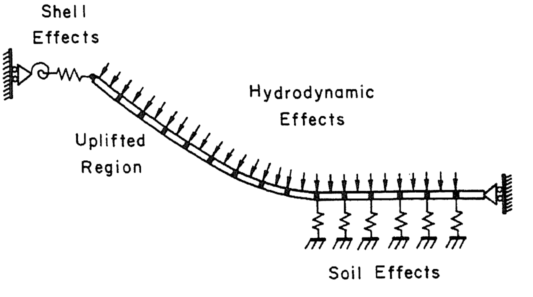

Fig. 2. Factors affecting the behavior of the base plate.

PRESENT STUDY

As noted, several attempts were made to model the extremely complex behavior of unanchored tanks but most models were either too simple to capture the fundamental response or too complicated by modeling so many features at once. The objective of the present study is to reproduce with a reasonable degree of accuracy the nonlinear response mechanisms revealed in past seismic events. The nonlinear behavior of the base plate under static and dynamic loading is analyzed. In addition, liquid sloshing which has a more pronounced effect on the response of unanchored than anchored tanks is also studied.

STATIC AND DYNAMIC BEHAVIOR OF THE BASE PLATE

Because the behavior of the base plate dominates the response of the overall system, the first phase of the study (Ref. 2) addresses the important factors which govern its nonlinear response. A parametric study is conducted to assess the influence of such factors on the plate response under both static and dynamic uplifting forces. The analysis differs from other available analyses in that the plate is modeled as a circular plate rather than being modeled as a strip plate, although some of the complicating factors were investigated by the strip model.

Strip Models The uplifting problem is nonlinear in nature because of the successive separation and contact of the base plate with the foundation. In the uplift region, the relation between the vertical deflection and the vertical uplift force is nonlinear because of the change in the contact area and because of the large deformation. In the contact area, the behavior of the foundation introduces a nonlinear effect because the area of contact is dependent on the load. Although the intent here is to rely on more reliable models to predict the response of the base plate, strip models are still used to provide initial insight to the effects of complicating factors such as the nonlinear contact with the foundation under the large deflection assumptions, the inelastic response of the plate and its behavior under impact. Also, since the uplift of the base plate may occur over a relatively short distance, this necessitates not only the assumptions of large deflections but also the recognition that the slope of the deflected shape of the flexible plate might as well be large. Hence, the equations which govern the plate deformation are derived under the assumption of large deflection and slope. Test cases for using the finite element methods in the analysis of the contact problem are performed.

Circular Models The base plate is represented as a circular model. Two methods of analysis are used, namely, an approximate energy-based approach and a more elaborate approach based on the finite element method. The energy methods offer a simpler alternative to the equilibrium method but the shape of the uplifted region and the distribution of vertical, radial, and tangential displacements of the plate which satisfy the geometric boundary conditions must be assumed. A sensitivity analysis of the accuracy of the results to the assumed displacement functions was performed. Both asymmetric model, in which the plate is assumed to be lifted off the foundation as a crescent-shaped region, and axisymmetric model, in which the

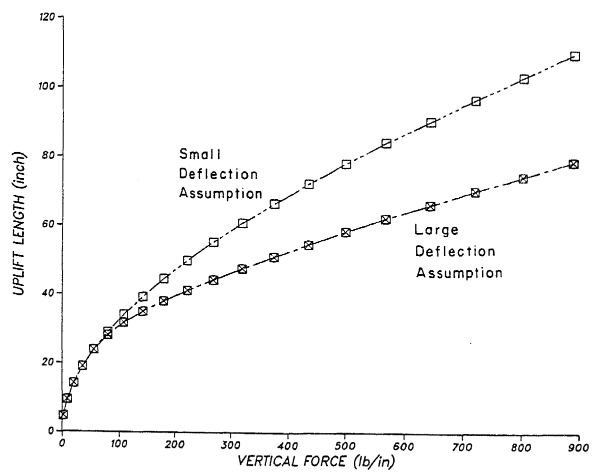

Fig. 3. Uplift length versus uplift force under small and large deflection assumptions.

plate is assumed to experience a uniform uplift all around the circumference, are used in the analysis. However, it is much simpler to perform the analysis under the axisymmetric conditions. This approximation has been proven correct since the deformations in the uplift region vary slowly in the circumferential direction. A computer program was developed to calculate the generalized displacements under the large deflection assumptions for a given set of external loads which cause the plate to lift. An iterative scheme was employed to solve the simultaneous, nonlinear, algebraic equations involved in the analysis. Further refinements of the computer program are being carried out to include the effects of the restraints that may be imposed on the plate at its outer edge, and to accurately calculate the internal forces throughout the uplifted region. A finite element model for the determination of the nonlinear force-displacement relation for the base plate was also developed to check the accuracy of the simplified model. The simple models are found to produce response with acceptable accuracy, and therefore, are more beneficial and attractive for use in practical design situations.

Dynamic Analysis of the Base Plate The nonlinear, time-dependent equations which govern the vibrations of the base plate are derived from Euler's equations. In deriving these equations, it should be noted that the kinetic energy is a function of the generalized coordinates and their time derivatives and that the mass of the liquid lifted by the plate contributes to the total kinetic energy. The resulting equations of motion of the plate are highly nonlinear. The solution of these equations is obtained by a step by step numerical time-integration technique with an iterative scheme at each time step. Special considerations are given to those instants where the plate impacts on the rigid foundation. The dynamic analysis of this study is novel because of the moving boundaries of the contact area.

HYDRODYNAMIC EFFECTS AND NONLINEAR LIQUID SLOSHING

The sloshing phenomenon in a large size liquid storage tank has been addressed in conjunction with the analysis of anchored tanks. For small amplitude oscillations, the coupling effect between the "low frequency" sloshing modes and the relatively "high frequency" shell modes, is insignificant. However, liquid sloshing may play an important role in influencing the integrity of unanchored tanks under seismic loadings. The influence of liquid sloshing is more pronounced for unanchored than anchored tanks, partly because of the apparent "low frequency" of the liquid filled tank as it rocks, and partly because of the large amplitude motion of the shell. The nonlinear response of the liquid is being investigated by performing the following tasks: evaluation of the effects of base uplifting on the hydrodynamic pressures; evaluation of the effects of the large-amplitude sloshing on the hydrodynamic forces exerted on the shell and the base plate; and analysis of the coupling between the "large amplitude, low frequency" shell motion with liquid sloshing motion.

CONCLUSION

The uplifting of the base plate of unanchored tanks is normally associated with large deflections which lead to the stretching of the middle plane of the plate, and consequently, induce membrane stresses. So far, the results have demonstrated that, under large static uplift forces, such membrane actions would increase the load carrying capacity of the plate considerably, and consequently, its maximum uplift displacement is significantly reduced. It was also noted that the analysis under axisymmetric conditions yielded results comparable to those of the asymmetric case though the latter analysis is much more complicated. In addition, it was proved that the flexibility of the foundation has a considerable influence on the uplift behavior of the base plate.

ACKNOWLEDGMENT

The present investigation is gratefully supported by the National Science Foundation (Grant No. CES-8706781) and is scheduled for completion in 1990. Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of NSF.

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