7th International Seminar on
Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures
Assisi, Italy, October 2-5, 2001

REVIEW OF ANALYTICAL AND NUMERICAL METHODS FOR SEISMIC EVALUATION OF SOME HIGH-RISK COMPONENTS AT PETROCHEMICAL FACILITIES

L. Dorfmann
Institute of Structural Engineering, Vienna, Austria
dorfmann@mail.boku.ac.at

P. B. Summers
MMI Engineering/GeoSyntec Consultants, Houston, USA
psummers@mmiengineering.com

P. P. Jacob
MMI Engineering/GeoSyntec Consultants, Houston, USA
pjacob@mmiengineering.com

J. Marti
Principia Ingenieros Consultores, Madrid, Spain
marti@principia.es

ABSTRACT

Concern for society, the quality of life of surrounding communities and the impact on the environment, forces policy makers to assess the risk of hazardous material releases from refineries and petrochemical facilities during earthquakes. In fact, a major seismic event in the vicinity of a petrochemical facility could damage (and has damaged in the past) process equipment, storage facilities and transfer (or lifeline) systems. The start of fires and the release of airborne toxic gases and/or volatile liquids may obstruct post-earthquake rescue and have major social and economic consequences.

In this paper a review is provided of analytical and numerical methods applicable for the seismic evaluation of one of the most critical components present in petrochemical facilities, that being deformable flat-bottomed storage tanks. The different types of such tanks and the different tank failure modes will be discussed. The need for reliable characterization of the fluid motion and the induced pressure distribution within a deformable structure subjected to seismic ground motion is important for anchored tanks to design proper anchorage systems and to evaluate possible shell buckling. For unanchored tanks, this information is even more critical to determine problems associated with a possible tank uplift, such as damage of over constrained connecting piping attachments, the buckling of tank walls because of vertical compressive stresses, and potential fracture at the junction between the bottom plate and the shell wall due to cyclic plastic hinge rotation.

INTRODUCTION

Unlike many other engineered structures, the seismic risk at petrochemical production and storage facilities is not only limited to the vulnerability of the component itself and the immediate danger to nearby human lives, but also extends to serious consequences and long-term effects for the surrounding communities, [1]. Past experience has shown that the loss of liquid contents from such structures, such as a tank containing highly inflammable and toxic petrochemical products, can lead to fires and contamination of the ground water, as well as the surrounding environment in general. Table 1 gives a short summary of the consequences of potential earthquake damage to petrochemical facilities and their potential effect on people, the environment and business.

A large amount of literature is available on methods and approaches to describe the behaviour of anchored and unanchored tanks. Investigations of tank damage due to earthquakes have shown that anchored tanks must be connected by a large number of anchor bolts to fairly massive foundations. The large number of bolts and corresponding attachments welded to the tank wall is necessary to allow the tension forces in the anchors to be distributed evenly in the tank wall. Improperly detailed attachments, or an attempt to carry too high a bolt force on a single attachment, could result in damage to the tank wall. Performance of anchored tanks during earthquakes has indicated that such tanks generally experience very few problems. However, since anchoring a tank is expensive, it is common practice to have the bottom tank plate rest on a compacted ground without the use of anchor bolts. This is especially true for large capacity tanks.

Some special issues regarding anchorage pertain primarily to large capacity cryogenic tanks, such as are utilized for LNG. If the seismic stresses are such that buckling of the inner tank could result, the following options generally exist:

1. Increase the thickness of the inner tank. This requires additional cryogenic steel and the welding of thicker elements.
2. Anchor the inner tank to the bottom slab of the outer tank. This can be expensive, provides a thermal bridge across a substantial fraction of the slab thickness, introduces complexities in the inner tank behaviour at the anchor welding points and creates construction delays and difficulties.
3. Provide some isolation between the outer tank and the ground, thus decreasing the level of seismic loading experienced by the tank. One then has to face the cost of the isolation system, a longer construction period and the problems of larger relative displacements at piping connections.
4. Few general rules can be given. In each case, the best solution must be reached, as a function of the local conditions, seismic demands, scheduling requirements, costs, etc.
5. Finally, in large cryogenic tanks, if anchoring is used, it takes place between the inner and outer tank, without involving the ground; this may be different for smaller tanks.

Additional information regarding earthquake issues at LNG tanks is given in [24].

Product Release to Atmosphere	Release of product into atmosphere to form cloud of toxic product (gas or particulate). Dispersion and dilution of cloud is dependent on local meteorological conditions. Impact to population if cloud is of sufficient size and in proximity to urban areas. Impact (injury or death) to plant personnel in immediate vicinity.
Product Release to Soil, Groundwater or Body of Water	Release of product into soil, groundwater or bodies of water. Adverse effect to environment by introduction of toxic agents. Extremely difficult to remove from environment (will require long duration activities) if products enter water table. Impact to population and wildlife by damage to environment.
Pool Fire	Ignition of product lying on ground. Potential for toxic cloud formation – product release to atmosphere. Fire damage to surrounding equipment. Traveling fire if pool is not contained. Impact (injury or death) to plant personnel in immediate vicinity.
Jet Fire	Locally concentrated fire issuing from rupture location. Localized intense fire damage to equipment. Potential for toxic cloud formation – product release to atmosphere. Impact (injury or death) to plant personnel in immediate vicinity.
BLEVE (Boiling Liquid Expanding Vapor Explosion)	Pressure vessel rupture leading to product release to atmosphere and missile formation from pressure vessel fragments. Damage zone from fragments dependent on magnitude and energy content of event. Potential for toxic cloud formation – product release to atmosphere. Impact (injury or death) to plant personnel in immediate vicinity.
Vapor Cloud Explosion	Detonation of vapor cloud. Explosive strength dependent on concentration of cloud and chemical reactivity of product. Ignition can occur from fires, BLEVE's and urban sources. Cloud detonation potential varies with local meteorological and geographical conditions.
Business Interruption Losses	Interruption to facility normal operations through damage to equipment resulting in loss of production and possible long-term loss of market share. Magnitude of interruption dependent on level of damage (time to repair) and ability to perform the required repairs and upgrade of the facility after the earthquake event.
Direct Economic Losses	Cost of direct economic losses to facility and surrounding community. This includes costs to re-build and clean up, and increased cost of future insurance premiums.
Indirect Economic Losses	Costs related to loss of public goodwill and credibility, exposure to insurance claims and litigation brought for personal injury and death, as well as damage to environment and property, and possible loss of employment for local population as facility is temporarily shut down and re-built, if possible. Impact to surrounding community both socially and economically.

Table 1: Consequences of Earthquake Damage to Petrochemical Facilities

The response of unanchored tanks is discussed in detail in [23] and in its predecessor papers, [21] and [22]. Much of the material below is taken from these sources. During earthquakes, the response of unanchored tanks is highly nonlinear and much more complex than implied in available design standards. The effect of seismic ground shaking is to induce tank sliding and tank uplift, thereby generating an overturning moment caused by hydrodynamic pressures. The weight of the fluid resting on the uplifted portion of the tank bottom, together with the weight of the tank shell and roof, provides the restraining moment against uplift. While uplift may not cause serious damage, it can be accompanied by large deformations and major changes in the tank wall stresses. Tank uplift during earthquakes has been observed many times, but the amount of uplift has rarely been recorded. For the 1971 San Fernando earthquake, a 0.3-meter uplift has been recorded for a 30-meter diameter and 20-meter high tank.

In general, tanks, especially unanchored tanks, are particular susceptible to earthquake damage, which may fall primarily into one of the following categories [21, 22, 23]:

1. Buckling of the tank wall, known as "elephant foot" buckling. This occurs because of high vertical compressive stresses in the portion of the tank wall remaining in contact with the ground. The compressive stresses are accompanied by bending stresses introduced in the shell wall because the baseplate prevents the radial deformation, which would normally occur under internal pressure. Unanchored tanks with D/H ratio of two and above tend not to have elephant foot buckling. As this ratio decreases, the propensity to elephant foot buckling increases.
2. Another common buckling mode, known as diamond shape buckling, is normally associated with taller tanks having H/D ratios of about two. In contract to elephant foot buckling, which is associated with permanent deformation, diamond shape buckling is a purely elastic phenomenon. A positive aspect of tanks which experience either elephant foot or diamond shape buckling is that the buckled tank often does not rupture and continues to fulfill its function of containing fluid.
3. During tank uplift, the baseplate may not possess sufficient flexibility for deformation continuity with the displaced shape of the tank Further, the weld between the baseplate and tank wall man not be able to accommodate the tension stresses that develop as a result of the fluid hold-down forces which are mobilized to resist uplift. In either case, fracture at the junction between the baseplate and tank wall may occur. Such failure can lead to rapid release of the tank contents.
4. Breakage of attached and overconstrained piping due to tank uplift and inadequate piping flexibility. This is one of the most prevalent causes of product loss from storage tanks during earthquakes. Pipe failures can also occur due to relative movement between two different tanks connected by rigid piping.
5. Tearing of tank wall or tank bottom due to overconstrained stairways anchored at the foundation and tank shell.
6. Tearing of tank wall due to overconstrained walkways connecting two tanks experiencing differential movement.
7. Damage to the tank floating roof or fixed roof followed by slippage of fluid over the tank walls. This can occur if insufficient freeboard is provided to accommodate sloshing of the surface of the tank contents. This type of damage is usually considered only minor but may be important for some stored products.

ANALYTICAL AND NUMERICAL EVALUATION

Methods for Analysis of Anchored Tanks

Housner in his pioneering work in 1957 developed a simplified method to describe the dynamic fluid pressure distribution in rigid anchored tanks on rigid foundations, [2]. Housner introduced the concept of impulsive and convective components for the generated hydrodynamic fluid pressures. The earthquake hydrodynamic forces generated by the vibrating fluid content can be separated into two components: the impulsive component and the convective component. The impulsive component is associated with the part of the liquid that moves in union with the tank shell, whereas the convective component arises form the sloshing part of the liquid that oscillates in its first mode. The Housner model was adopted as the basis for the seismic design provisions in the commonly used design standards API [3] for oil storage tanks and AWWA [4] for water reservoirs.

Additional early experimental studies and theoretical research, which focused mainly on the simpler problem of anchored tanks, resulted into a good understanding of the hydrodynamic fluid-structure interaction effects between the vibrating liquid content and the rigid and/or flexible tank shell, [5, 6]. The vibrating liquid generates a hydrodynamic pressure and thereby an overturning moment at the base. This overturning moment will increase the axial compression in the shell on one side of the tank and generate tensile forces on the opposite side. The axial compression in the tank shell tends to buckle the wall resulting into the well-known elephant foot buckling mode.

Past performance of anchored tanks during earthquakes have indicated that such tanks generally experience very few problems. The reason for it is that very few tanks were anchored before seismic provisions of API 650 were introduced in the late 1970's [7], and those that were subsequent anchored were designed to those very same provisions.

Anchored tanks should be considered as adequate unless anchorage details are judged to be capable of tearing the tank shell or bottom plate, causing loss of contents. Anchorage details should be assessed during walkthrough inspection to ensure that there is an adequate load path for the hold-down forces developed in the anchor bolts to be transferred from the tank shell to the foundation. A reference on how to numerically quantify anchored tanks can be found in [3], [8], [9] and [23].

Methods for Analysis of Unanchored Tanks

More recently, research has focused on understanding the more complex seismic response of flexible unanchored tanks, which are free to uplift during earthquakes. The uplift mechanism of the tank and the fluid motion of the content are highly nonlinear and much more complex than implied in available design standards. The literature is extensive on the seismic design and analysis of flexible flat-bottomed tanks. It is not our aim to provide a full summary on the available literature on this subject, but the interested reader is referred to [10, 11, 12, 13 14, 15, 16] and the references therein. However, there are only a few practical methods available for analyzing unanchored tanks. Some of these methods are:

1. API 650 Appendix E [3]: This method is the standard for design of new tanks for the petrochemical industry. It is simple to use and its provisions generally match those of the Uniform Building Code (UBC), [17].

2. AWWA D100, [4]: This method is very similar to the API 650 method, and is used primarily for design of water storage tanks.
3. Earthquake Tank-Wall Stability of Unanchored Tanks, [18]: George Manos has developed an alternative method of assessing tanks, which is significantly different to the previous two methods and is based on observed performance of tanks during past earthquakes. Additional commentary is provided in [21, 22, 23].
4. Seismic Design of Storage Tanks, [19]: This method was proposed as the tank design code for New Zealand.

API 650 TANK EVALUATION METHODOLOGY

The seismic design methodology for welded steel storage tanks presented as API Appendix E is based on a simplified procedure developed by Housner [1, 20]. The procedure considers the overturning moment on the tank to be the sum of

1. The overturning moment due the tank shell and roof, together with a portion of the contents, which moves in unison with the shell, acted on by a horizontal acceleration. The value of the acceleration can be taken as the peak of the 2% damped site response spectrum, divided by a factor that accounts for the ductility and reserve capacity of the tank. Alternatively, the code allows a value of 0.24g to be used for the highest seismic zone. This is termed the impulsive component. The impulsive response is thus caused by the portion of the fluid accelerating with the tank
2. The overturning moment due to that portion of the tank contents which moves in the first sloshing mode, acted on by a horizontal acceleration equal to 0.5% damped spectral acceleration corresponding to the period of that mode, again divided by a ductility/capacity factor. Alternatively, the code provides simplified formulas to determine the acceleration to be used. This is termed the convective component, i.e. response caused by the portion of the fluid sloshing in the tank.

Resistance to the overturning moment is provided by the weight of the tank shell and roof and by the weight of a portion of the tank contents adjacent to the shell. The structural adequacy of the tank is determined by a stability ratio, which is a measure of the ratio of the overturning moment to the resisting moment. The value of the stability ratio must not exceed 1.57. Further, reference [3] provides a methodology for calculating the compressive stress at the bottom of the tanks shell together with the maximum allowable value of shell compression; the latter corresponds to approximately one-third to on-half of the theoretical buckling stress of a uniformly compressed perfect cylinder. If the stability exceeds a stability ratio of 1.57 or the compressive stress exceeds the allowable value, retrofit of the tank or reduction of the liquid height is necessary.

Extensive experimental studies and observations during past earthquakes have demonstrated that the API uplift model substantially underestimates the actual liquid weight resistance, which is mobilized during uplift. The reasons for this are that the API model does not account either for the in plane stress in the bottom plate, or for the dynamic nature of the tank response. The model also calculates an unrealistically narrow compression zone at the toe of the tank, thus leading to large compressive stresses in the tank shell for relatively low overturning moments. Finally, the API approach does not account for the effect of foundation flexibility on the tank wall axial membrane stress distribution.

Although the API methodology is known to be conservative and condemning existing tanks for failing to meet the API criteria may not be deemed appropriate, the criteria are the basis of the current seismic design practice and serve as a good benchmark. Gross violations of specific provisions should be taken as an indication that retrofits are necessary.

ALTERNATIVE METHODOLOGY

As an alternative to the API methodology described above, a modified version [21, 22, 23] of a method for evaluation of unanchored tanks, developed by George Manos is briefly reviewed here. Manos' method [18] is based on experimental studies, as well as on observed behavior of unanchored tanks during past earthquakes. Based on the experimental evidence, an empirical axial compressive stress distribution is assumed around the toe of the tank. The compressive stress is a maximum at the toe (opposite the point of maximum uplift), and decreases to zero at an empirically determined distance from the toe. The compressive stress at the toe is limited to 75% of the critical buckling stress of a uniformly compressed perfect cylinder. Integration of the assumed axial stress yields a resultant compressive force, which must be balanced by an equal tensile force due to the weight of the fluid resting on the uplifted portion of the baseplate. Using an empirical formula for the lever arm between these two forces, an expression for the resisting moment against uplift of the tank is developed. Additional resistance provided by the weight of the tank shell, the bending moment distribution in the tank wall, and other sources are ignored.

The overturning moment on the tank is calculated in a manner similar to that used in the API methodology, except that the convective component of the overturning moment is neglected for simplicity. This is felt to be appropriate since, because of phase differences between the impulsive and convective components, the convective portion is not believed to contribute much to the peak tank wall stress response, especially for very tall tanks. This omission is balanced somewhat by ignoring some portion of the overturning resistance, as described above and by the use of an expression for the height of the center of mass of the fluid that is slightly conservative.

The tank is deemed to be stable if the limit resisting moment is greater than the earthquake induced overturning moment.

The method for evaluation of unanchored storage tanks recommended [22, 23] herein is based on that of Manos, but includes some important variations. The most notable of these are:

1. Tank anchorage is recommended whenever the ratio of safe operating height to tank diameter exceeds two. Based on the data presented in [18], and the higher level of risk for taller tanks, this is believed to be the upper limit of applicability of the Manos method.
2. The allowable compressive stress in the tank shell is increased from 75% to 90% of the theoretical bucking stress. However, the compressive stress should not exceed the material yield stress. Examination of the experimental and observational data presented by Manos [18] indicates that this increase is justified for the types of tanks encountered at petrochemical storage facilities.
3. The compressive force in the tank shell should not exceed the total weight of the fluid contents. This has the effect of imposing an upper bound on the resisting moment.

An important feature of the modified Manos methodology is the use of a foundation deformability coefficient. This should be taken as 1.0 for tanks founded on more rigid materials, such as concrete, asphalt rings or pads, and 1.2 for materials founded on crushed rock, wood planks or soil. The effect of this is that the size of the compressive stress zone is larger for a soft foundation than that for a rigid foundation. This enables the development of a larger limit resisting moment (subject to the limitation imposed by the total weight of the fluid, as described above) and, consequently, enables the tank to withstand a large seismic acceleration. This contrasts with the API methodology, where the soil type has no influence on the resisting force which can be developed, but where a softer soil leads to a larger convective acceleration and hence an increased overturning moment.

CONCLUSIONS

A brief overview and summary is given to describe the performance of anchored and unanchored flexible storage tanks subjected to seismic ground motion. The paper summarizes first the consequences of potential earthquake damage to petrochemical facilities and their potential effect on people and environment. Next, the damages most often observed in tanks, especially unanchored tanks are briefly described and quantified. In the second part of the paper a brief overview is provided of the analytical and numerical evaluation methods for flexible anchored and unanchored storage tanks. Even though a large number of experimental results and numerical evaluation methods have been published in the literature over the last several decades, only a few practical methods are available for the practicing engineer to design petrochemical storage facilities in high risk seismic areas.

REFERENCES

1. Lau, D.T., Marquez D. And Qu, F., Earthquake Resistant Design of Liquid Storage Tanks. Eleventh World Conference on Earthquake Engineering, 1996. Paper No. 1293.

2. Housner, G.W., Dynamic pressures on accelerated fluid containers. Bulletin of the Seismological Society of America, 53, pp.381-387, 1957.

3. American Petroleum Institute, API 650, Eighth Edition, Welded Steel Tanks for Oil Storage. Appendix E, Seismic Design of Storage Tanks, 1993.

4. American Water Works Association, ANSI/AWWA D100-84. AWWA Standard for Welded Steel Tanks for Water Storage, 1985.

5. Haroun, M.A. and Housner, G.W., Seismic Design of Liquid Storage Tanks. J. of the Technical Councils of ASCE, 107, pp 191-207, 1981.

6. Veletsos, A.S., Seismic Response and Design of Liquid Storage Tanks. In: Guidelines for the Seismic Design of Oil and Gas Pipeline Systems, pp. 255-365, 1984, ASCE, New York.

7. R. S. Wozniak and W. W. Mitchell, Basis of Seismic Design Provisions for Welded Steel Oil Storage Tanks. Presented at the Session on Advances in Storage tank Design, API Refining, 43rd Midyear Meeting, Toronto, Canada, May 1978.

8. American Society of Civil Engineers, Guidelines for the Seismic Design of Oil and Gas

Pipeline Systems. Committee on Gas and Liquid Fuel Lifelines, New York, New York 1984.

9. Housner, G. W. and Haroun, M. A., Seismic Design of Liquid Storage Tanks, ASCE Convention and Exposition, Portland, Oregon, April 14-18, 1980.

10. Haroun, M.A., Tayel, M.A., Response of Tanks to Vertical Seismic Excitations, Earthquake Engineering and Structural Dynamics, 13, pp. 583-595, 1985.

11. Rammerstorfer, F.G., Scharf, K. and Fisher, F.D., Storage Tanks under Earthquake Loading, Applied Mechanics Reviews, 43, pp.261-281, 1990.

12. Fisher, F.D., Rammerstorfer, F.G. and Scharf, K., Earthquake Resistant Design of Anchored and Unanchored Liquid Storage Tanks under Three-Dimensional Earthquake Excitation. In Structural Dynamics, Recent Advances, ed. G.I. Shueller, 317-371, Springer Verlag 1991.

13. Vestsos, A., S., Tang, Y., Tang, H., T., Dynamic Response of Flexible Supported Liquid Storage Tanks, ASCE, Journal of Structural Engineering, 118, pp. 264-283, 1992.

14. Chen, W., Haroun, M.A., Liu, F., Large Amplitude Liquid Sloshing in Seismically Excited Tanks, Earthquake Engineering and Structural Dynamics, 25, pp. 653-669, 1996.

15. Malhorta, P., K., Seismic Response of Soil-Supported Unanchored Liquid-Storage Tanks. ASCE, Journal of Structural Engineering, 4, pp. 440-450, 1997.

16. Wunderlich, W. and Rapolder M., Numerical Treatment of the Dynamic Soil-Structure-Fluid Interaction of Unanchored Liquid Storage Tanks, IUTAM Symposium on Discretization Methods in Structural Mechanics, eds. H.A. Mang and F.G. Rammerstorfer, pp. 99-106, 1999.

17. International Conference of Building Officials, Uniform Building Code, Whittier, CA, 1997.

18. George C. Manos, Earthquake Tank-Wall Stability of Unanchored tanks. American Society of Civil Engineers. Journal of Structural Engineering, Volume 112, No. 8, August 1986.

19. Study Group of the New Zealand National Society for Earthquake Engineering. Seismic Design of Storage tanks. M.J.N. Priestly (Editor and Chariman) et al. December 1986.

20. Housner, G. W., Dynamic Pressures on Accelerated Fluid Containers. Bulletin of the Seismological Society of America, Volume 47, pp. 15-35, October 1977.

21. Dowling, M.D., and P.B. Summers, 'Assessment and Mitigation of Seismic Hazards for Unanchored Liquid Storage Tanks', Independent Liquid Terminals Association Bulk Liquid Transfer and Above-Ground Storage Tank Terminals Conference, Houston, Texas, 1993.

22. Summers, P.B., and P.A. Hults, 'Seismic Evaluation of Existing Tanks at Grade', American Power Conference, Chicago, Illinois, 1994.

23. American Society of Civil Engineers, 'Guidelines for the Seismic Evaluation and Design of Petrochemical Facilities', Washington D.C., 1997

24. Summers, P., Dorfmann, L., and J. Marti, 'Overview of Applications of Innovative Earthquake Resistant Design and Retrofit at Oil Refineries and Petrochemical Facilities', 7th International Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures, Assisi, Italy, October 2-5, 2001.