State of art - Seismic Analysis of Oil Storage Tanks

Reenu Pascal[1], Dr C. K. Prasad Varma Thampan [2]

[1] *PG Scholar, Department of Civil Engineering, NSS College of Engineering, Kerala, India*
[2] *Professor, Department of Civil Engineering, Kerala, India*

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Abstract - *Liquid storage tanks are used to store chemicals in various industrial plants. They mainly found application in various power plants for storing oil, water for various requirements. While considering with other structures these structures comes in contact with liquid and hence its response under seismic load is quite different. Along with the hydrostatic pressure the seismic force imparts hydrodynamic pressure. This liquid structure interaction has got its importance in the design of cylindrical tanks and hence during design, due consideration should be given. Seismic behavior of tanks is greatly affected by the height to diameter ratio, fluid height and fluid type, thickness of tank, height to thickness ratio etc.*

Key Words: oil, hydrostatic, hydrodynamic

1. INTRODUCTION

Storage tanks can be mostly seen in refineries and chemical plants which contain large volumes of flammable and hazardous chemicals such as petroleum, crude oil, LNG etc. A small accident may lead to catastrophic accident, massive property loss and a few days of production interruption (Chang & Lin, 2006). For avoiding the adverse consequences such as fires, explosions and environment pollution, war, calamities, it is very necessary to have a better understanding of their seismic behaviour. In last decades, strict engineering guidelines and standards for construction, seismic design and safe management of storage tanks and their accessories were published by trade organizations and engineering societies such as the American Petroleum Institute (API), the American Institute of Chemical Engineers (AIChE), the American Society of Mechanical Engineers (ASME), and the National Fire Protection Association (NFPA). Companies usually follow these standards and guidelines in design, construction and operation, but tank accidents still occur (Chang & Lin, 2006). Failure mechanisms reported on storage containing structures depend on different factors that we have seen above, and the design of these tanks will depend on some factors. These factors include the configuration, shapes the construction material and the supporting system method of construction. The configuration depends on the usage purpose of the tank. Based on the shapes it can be circular, rectangular, square, cone-shaped or other shapes. Steel and concrete are the most common construction materials. Concrete tanks can be again classified as cast-in-place, pre-tensioned or post-tensioned. Furthermore, the method of construction also matters. The next contributing factor is the supporting system, as the tank can be elevated, anchored or unanchored into the foundation or underground type. The roof can be open, fixed or floating type. The various other type of tank that includes Bullet tank, Bolted tank and Sphere Tank.

1.1 Basic Concepts

The tank can be rigidly and flexibly attached to the ground. Consider that the tanks are assumed to behave as rigid bodies, rigidly attached to the ground. Consequently, during horizontal ground acceleration, the tank wall and floor respond as part of, and in unison with, the moving ground. The inertia forces due to horizontal acceleration of the rigid wall and floor is directly proportional to the ground acceleration. When the accelerating tank is full, the lower portion of the contained liquid, Wi, acts as if it were a solid mass rigidly attached to the tank wall. As this mass accelerates, it exerts a horizontal force against the wall directly proportional to the maximum acceleration in the tank bottom. This force is identified as an impulsive force, Pi. The upper region of the contained liquid act as a solid oscillating mass flexibly connected to the tank wall under the same accelerations. This portion, which oscillates (sloshes) at its own natural frequency, exerts on the wall an additional force that is proportional to the square of that frequency, as well as to the ground acceleration. This portion is defined as the convective component Pc. The convective component oscillations are characterized by the "sloshing" action whereby the liquid rises above the static level on one side of the tank, and drops below that level on the other. This procedure is valid only for rigid tanks on rigid foundations. Whereas the walls of rigid tanks move in unison with the ground, motion of flexible tanks is different. Flexibility affects the hydrodynamics effects and may increase the seismic characteristics significantly.

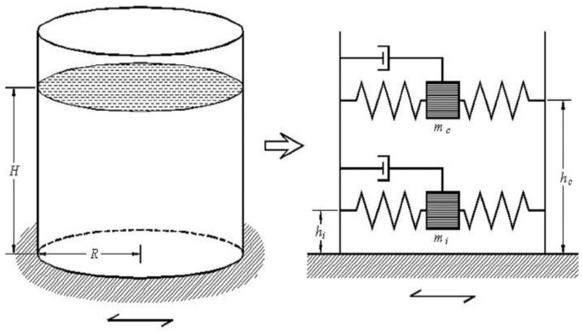

Fig -1: Mathematical Model

1.2 Sloshing

Any kind motion that can happen on the free liquid surface inside a liquid storage tank which is called Sloshing.

This disturbance mainly happens to partially filled liquid containers. Liquid sloshing on the free surface has got significant influence on the response of the storage tank. The estimation of hydrodynamic pressure distribution, forces moments and natural frequencies of the free-liquid surface are the major problems while considering the liquid sloshing. To model the sloshing part, the various mechanical models are used such as mass-spring-dashpot or pendulum systems. In the past several decades, sloshing waves have been studied. Many significant phenomena such as the linear and nonlinear effects of sloshing for both inviscous and viscous liquids have been considered in those studies.

2. COMMON DAMAGES

2.1. Bottom of Tank Uplifting

When an unanchored tank is exposed to strong ground shaking, the overturning moments occur which cause hydrodynamic pressure, and its one side is up lifted unless the weight of the tank can be balanced and prevents uplifting during the overturning moment. The effects of several parameters such as axial force existing on the tank bottom plate, the large deformations of the tanks wall, tank-soil-fluid interaction, large deformations of the tank wall caused by surface waves, membrane pressures in and bottom of the tank, shell geometric imperfections, and flexible foundation in the analysis of steel tank are considered to the process of complex uplifting phenomenon and its completed description. This phenomenon is resulted in several different factors. The high ratio of height to diameter, low thickness of wall of the tank bottom and shell thickness are effective factors in the damaging mechanism. The allowable uplifting amount in the unanchored tanks based on existing instructions has been limited to 30 cm. If the allowable amount exceeds, it will cause to rupture the tank wall, break input-output pipes, and centralize the wall tension in the local connection or subside the asymmetry of foundation.

Fig -2: Uplifting Phenomenon

2.2. Shell Buckling

A) Elastic buckling (Diamond wall) that caused by the compressive pressures made in the tank wall and in the middle part of the high altitude tanks.

B) Elastoplastic buckling (Elephant foot) that caused by the tensions resultant resulting from the tank overturning and uplifting power and annular tension caused by the hydrostatic pressure of the fluid at the height of 1.5m to 2.5m from the bottom of the tank. To prevent elastic and Elastoplastic buckling damage, increase in the compressive pressure created in the tank wall, and the excessive increase of annular tension in the tank wall should be prevented, respectively. Therefore, this control is done by comparing these tensions with the amount of wall allowable pressures stated according to bylaws codes API 650.

Fig -3: Shell Buckling

2.3. Asymmetric Subsidence and Slip

Subsidence in tank can happen due to the dynamic forces that was caused due to the collision between the bottom of the tank and foundation during earthquake. Based on existing instructions, the amount of allowable subsidence is limited to 5 cm. The shear force caused by the earthquake at the bottom level of the tank may overcome on the friction force between the tank bottoms and the foundation and cause to slip the tank. In order to control the tank against slip, foundation cutting is considered as a driving force and tank bottom friction force against the bed is considered as a counterpoise. According to the proposal of ASCE instructions, the minimum safety factor which is needed against the slip equals 1.5. To calculate the counterpoise against the slip, the friction coefficient between the tank bottom and foundation is suggested equal to 0.4. This damage occurs more in tanks with diameters smaller than 9 meters.

2.4. Damaged Tank Foundation

In many cases, the tanks are located in areas that are not suitable place to build a tank geotechnical. In the unanchored tanks or tanks have been incompletely anchored, and have solid foundation, failing in welds of the bottom of tank plates is expected. Therefore, earthquake acceleration causes that part of the tank in which the tensile force has been created to uplift. Sometimes the tank pouring out causes erosion in the tank foundation; therefore, the tank during the earthquake shows more undesirable behavior. A common failure here is the bottom of tank distortion near the tank wall, which can be occurred due to soil liquefaction, slopes instability or excessive subsidence. This damaging can be prevented by density of the soil of tank installation location and using widespread armed foundation under the tank. Tanks manufacture on flexible foundation is more suitable than their implement on a rigid foundation. Because the soft foundation causes the period of tanks vibration against the hydrodynamic forces to be prolonged.

2.5. Overturning

Moment of overturning which is occurred as a result of the earthquake based on tank can cause part of the tank bottom plate to be uplifted, so seismic response of this type of tanks exits from the linear range, and enters to the non-linear phase. With increase height to diameter ratio of the tank, the overturn moment will be increased, so its stability will be reduced. That is due to the increase in the distance between the centre of mass from the bottom. This criterion is controlled by using Appendix E from bylaws of API 650 and based on M/ (Wt+WL) ratio. In this formula M is tank overturning moment on Newton meters, WL is the weight of the tank contents on perimeter length unit which resists against overturning, and Wt is the weight of wall plate in tank in thickness unit on Newton meters. Thus, if the ratio is greater than 1.57, tanks will be unstable and overturned against loads.

2.6. Roof Damaging

Tank structure and fluid vibrates due to the force caused by the earthquake, consequently, it makes waves in its fluid surface. Fluid vibration is happened when the frequency is much lower than the frequency of the wall, and vibration amplitude of fluid is affected by the frequency of earthquakes. Therefore, if these issues are not predicted, the tanks roof cover may be damaged or its contents are emptied out. If the free distance of the fluid is not enough, the structure will be damaged. In order to control the fluid volatility (sloshing) and the roof damage, fluid free height (Free board) can be increased, or the tank roof be reinforced. According to API 650 bylaws, the required free height is equivalent to 70% of the wave height. Sometimes because of failing the connection between the wall and the bottom of tank, or failing the pipe connected to the tank, tank fluid is depleted quickly; as a result, the rapid discharge of fluid above the fluid level makes partial vacuum which damages the roof and the upper part of the tank shell.

Fig -4: Roof Damage

3. LITERATURE REVIEW

Housner (1963) is the one who modelled the dynamic behavior of tanks for the first time, and it has become the base for designing constitutes. He found that Impulsive and Convective pressures would be affecting the tank wall when a free surface tank is exposed to lateral dynamic acceleration, as shown in Fig 5. Convective movement comes from turbulent fluid over the tank that creates sloshing in tank, and impulsive pressure is applied as a part of fluid moves at the bottom of tank consistent and rigidly with the shell. In fact, frequency of convective movement is considerably higher than the frequency of impulsive movement, that is, this mode is stimulated in higher earthquake periods. The various assumptions in this model

a) Walls are rigid,

b) The fluid is incompressible, and

c) Fluid displacements are small.

In this model, by concentrating the mass of the tank at two points, a ground-supported liquid storage tank and an elevated can be idealized as a system with two-degree of-freedom. The functions of the geometry of the tank and fluid elevation are masses and stiffness. Hence to investigate the seismic response of the liquid storage tanks, this model has been widely and most commonly used.

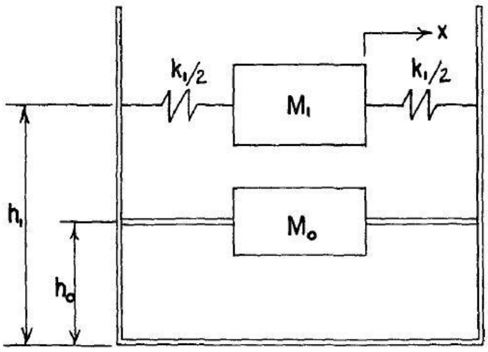

Fig -5: Equivalent Dynamic system for Water Tank

An assumed mode method has been put forward by Veletsos (1974) and the idea of this method is to simplify the liquid storage tank into a single degree of freedom system. On the assumption that the wall vibrates in accordance with the pre-assumed deformation vibration model, the inertia force of fluid to the tank wall is considered equivalent to added mass attached to the wall. This method was developed into Veletsos Yang model in 1976 which is simplifying the model into a one-dimensional cantilever. In the calculation of the dynamic response of liquid storage tank it has become as one of the most commonly used methods. Veletsos used Flugge's shell element theory to analyze the elastic liquid storage tank. Displacement of any point on the wall was represented by the superimposed inherent vibration modes of the cantilever. Part of the liquid attached to the tank wall was built to simulate the contact interaction of the liquid and the wall. They had also shown that the impulsive liquid should experience accelerations that are several times greater than the peak ground acceleration due to flexibility of the tank wall. Thus the base shear and overturning moment calculated can be considered as non-conservative by assuming the tank to be rigid. Later a three-mass model of ground-supported tanks have been developed by Haroun and Housner (1981) which takes tank-wall flexibility into account. Veletsos and Tang (1990) found out that tanks supported on flexible foundations, through rigid base mats, experience base translation and rocking, resulting in longer impulsive periods and generally greater effective damping. These changes may significantly affect the impulsive response. Due to the long period of oscillation, the convective or sloshing response is insensitive to both the tank wall and the foundation flexibility. Anestis S. and Veletsos et al. (1992) tried to focus on dynamic response of flexibility supported liquid storage tanks. Also critical responses are evaluated for harmonic and seismic excitations over wide ranges of tank proportions and soil stiffness, and the results are used to elucidate the effects of soil-structure interaction. It is shown that the critical responses of broad tanks can be significantly reduced due to soil-structure interaction, but the response has increased in tall, stiff tanks that have high fundamental natural frequencies. It has also shown that the higher modes of vibration have become an insignificant contributor to the overall response of tank for tanks with height-to-radius ratios of 1.5 or less. Mohsen Mohamadshahi and Ali Afrous (2015) found out that the tanks that have not designed or detailed adequately may suffer serious damages during earthquake. The various seismic damage modes in liquid storage tanks are buckling of side walls (diamond buckling), failure of tank roof and their junction, failure of anchor bolts, sliding and lifting, elephant foot buckling of tank wall at bottom, and uneven settlement, etc.

Fig -6: Elephant foot buckling

In studies of Malhotra and Veletsos (1994), the effects of base uplifting on the seismic response of partially anchored and unanchored tanks supported on rigid foundations were therefore studied. It was shown that base uplifting reduces the hydrodynamic forces in the tank, but increases significantly the axial compressive stress in the tank wall. Later Malhotra (1995) analyzed the base uplifting in tanks supported directly on flexible soil foundations and found out that it does not lead to a significant increase in the axial compressive stress in the tank wall, but large foundation penetrations and several cycles of large plastic rotations at the plate boundary will get happened. And hence it concludes that in flexibly supported unanchored tanks, uneven settlement of the foundation and fatigue rupture at the plate-shell junction would happen more but elephant-foot buckling damage was very less. Malhotra (1997) also demonstrated the significant reduction in both the overturning base moments transferred to the foundation and the axial compressive stresses in the tank wall due to the effective usage of isolation. He analyzed the seismic response of base-isolated steel tanks and found that the response of the tanks can be effectively reduced using isolation over the traditional fixed base tank which will not show significant change in sloshing displacement. Malhotra (1998) also conducted research on usage of dissipating anchors for seismic strengthening of tanks. Numerical results are obtained for two steel tanks supported on soil bed and anchored to the surrounding ring foundation by steel hysteretic dampers. During low-level shaking, the tanks behave as fully anchored systems but during strong shaking, the base of the tanks uplifts, and causing dissipation of seismic energy by inelastic action of the steel dampers. Energy-dissipating anchors can thus increase the effective damping in liquid-storage tanks to more than 20%. Later Praveen K Malhothra, Thomas Wenk and Martin Wieand (2000) proposed a theoretical background of a simplified seismic design procedure for cylindrical ground-supported tanks. The impulsive and convective (sloshing) actions of the liquid in flexible steel or concrete tanks fixed to rigid foundations has been taken in account in this procedure. Site response spectra is used and various seismic responses such as base shear, overturning moment, and sloshing wave height are calculated. Thus Eurocode has adopted this simple procedure. Wang et al. (2001) used Friction Pendulum System (FPS) for isolation of liquid storage tanks and investigated the response. He observed that this kind of isolation effectively reduces the response of the tanks. Panchal and Jangid (2008) proposed a new friction base isolator for seismic isolation of liquid storage steel tanks under near-fault ground motions and named it as Variable Friction Pendulum System (VFPS). Abali and Uçkan (2010) made a parametric study of liquid storage tanks isolated by curved surface sliding bearings and he had computed the sensitivity of critical response parameters such as, tank aspect ratio, period of isolation, and the coefficient of friction of sliding bearings to various ground motions. Shrimali and Jangid (2002) used lead-rubber bearings for isolation and investigated the seismic response of liquid storage steel tanks by under bi-directional earthquake excitation and he has observed that the seismic response of isolated tanks should not be sensitive to interaction effect of the bearing forces. Koeller and Malhotra (2003) examined seven unanchored tanks with different height to radius ratio and found out a close relationship between height to radius ratio and plastic rotation of tanks. K. C. Biswal, S. K. Bhattacharyya and P. K. Sinha (2006), modelled a two dimensional rigid rectangular tank with rigid baffles and used finite element method for computing the non-linear sloshing response of liquid. The potential formulation is considered for the liquid domain and a mixed Eulerian–Langrangian scheme is adopted. The solution is obtained by the Galerkin method. The fourth-order Runge–Kutta method is employed to advance the solution in the time domain. A re-gridding technique is applied to the free surface of the liquid, which effectively eliminates the numerical instabilities without the use of artificial smoothing. The values are compared with the available results for the rectangular tank without baffle, validation is done and then extended to the solution of tanks with rigid baffles. It has examined the various effects of baffle parameters such as position, dimension and numbers on the non-linear sloshing response. A circular cylindrical container with annular baffle is also modelled and the numerical solution procedure is also applied to the non-linear sloshing problems in these tanks. Jadhav and Jangid (2006) used elastomeric bearings and sliding systems for isolation and investigated the seismic response of liquid storage steel tanks under near-fault ground motions and observed that both elastomeric and sliding systems were effective in reducing the seismic forces of the liquid storage tanks. Zhuang Zhuo and Xiaochuan You (2006) simulated the dynamic response of large liquid storage tank under seismic load using finite element software ABAQUS. Based on Housner and Veletsos added mass formula, by introducing user subroutine UEL, they achieved added mass method in ABAQUS and by using energy principle they analyzed the occurrence mechanism of the "elephant foot effect" and "diamond effect". Waghmare, Birajdar and Pathak (2008), studied the seismic response of the cylindrical storage tanks. Finite elements are used for the liquid and tank wall. They considered elevated water tanks of capacity 120 m3. The staging height is varied from 25 m. to 5m. The sloshing phenomenon is studied for various depths of water in container, i.e., full, ¾, ½ and ¼. Modal analysis and response spectrum analysis were performed using ANSYS. On increasing the height of the staging the displacement of water goes on decreasing, but at certain stage the response again increases. It is interesting to note that for tank filled up-to 70% of its capacity the behavior is totally different i.e. as the height of the staging is increased, the displacement of water also increases up-to certain stage and then the response dies out. It is also very important to note that for the tanks are filled up-to 50% and 70% of their capacity the amount of displacement is more than the tanks are filled up-to 30% and 100% of their capacity. M. Moslemi, M.R. Kianoush (2012) made a parametric study on dynamic behavior of cylindrical ground-supported tanks. The dynamic behavior of cylindrical open top ground-supported water tanks is investigated. Both time history and free vibration analyses are carried out on concrete tank models with different aspect ratios. Time history response of both rigid and flexible tanks having different conditions at the base; fixed and hinged under both horizontal and vertical components of earthquake is obtained using the direct integration method. Based on these computed results, recommendations are made on the seismic design of cylindrical liquid tanks. It is concluded that the current design procedure is too conservative in estimating the hydrodynamic pressure. Hossein and Mehrpouya (2012), done both response spectrum and time history analysis on oil storage tank. They also checked the seismic vulnerability of the tank and found out that the freeboard level of tank plays a major role in the seismic performance of the storage tanks. Its significance depends on H/D ratio of the tank. According to seismic vulnerability analysis by using finite element method (FEM) and linear and nonlinear static and dynamic analysis, sloshing wave height does not effect on increasing of shell stresses and the main reason for shell stress increasing is uplift and settlement of tank bottom during earthquake. Maximum sloshing liquid wave height in the tank is also found out by various parametric study such as H/D ratio and liquid level of fluid in the tank. In tank with constant diameter, sloshing wave height increases by increasing liquid level in tank.

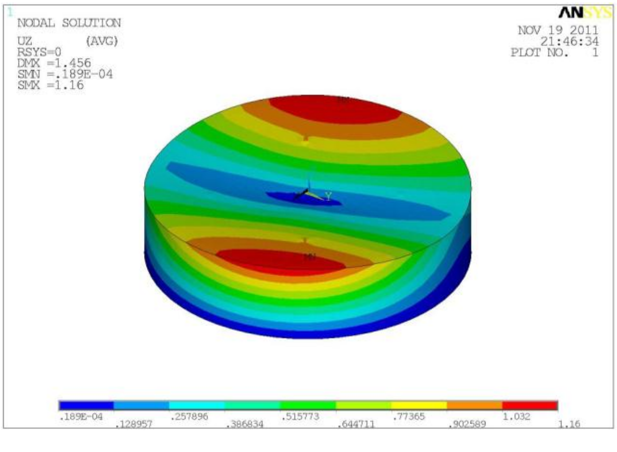

Fig -7: Maximum fluid wave height

In the paper Sharma et. al (2013), a parametric study is conducted on a Spring mass model and examined the various responses such as Time period in impulsive and convective mode, Design horizontal seismic coefficient, Base shear and Hydrodynamic pressure due to impulsive and convective mass of water. It has been found that under influence of seismic forces with increasing ratio of maximum depth of water to the diameter of tank (h/D), more mass of water will excite in impulsive mode while in decreasing ratio of (h/D), more mass of water will excite in convective mode. The Time period of Impulsive mode increase with increase in (h/D) ratio and Time period in convective mode decrease with increase in (h/D) ratio. It is very important to note that maximum hydrodynamic pressure on wall of tank in area located in Zone-V will have 3 to 3.5 times the maximum hydrodynamic pressure of an identical tank in Zone-II. Parvathy and Jini (2014) found out the modal analysis and response spectrum analysis of cylindrical fuel steel storage tank under seismic effect. They analyzed it by means of ANSYS finite element software. A fuel storage tank with diameter of 10m and height of 11m is considered for seismic analysis. Four different liquid filling levels (25 %, 50%, 75%,100%) is also considered. API Code is used for designing the tank. Using IS 1893:2002 (Part 2), the seismic analysis of fuel storage tank was calculated and parametric study by changing the aspect ratio were done. Using ANSYS Workbench software package, modal analysis was carried out on all four tanks considered. To study the effect of fluid level on tank behavior, Response spectrum analysis was also carried out on fuel storage tanks. And they found that tank with filling level other than 75% has got its normal stress in y- direction exceeds the minimum yield strength. Thus they concluded that 75% filling level is considered safe under seismic effects.

3. CONCLUSION

Oil storage tanks are extensively used structures, which sustain effectively the loads caused by their contents during static conditions, but they are subjected to severe loading during strong earthquakes. This can lead to material strength failures or buckling failures leading to loss of contents. In order to design structures properly the response of the tank and its contents under base excitation must be known. The various kind of failure that can happen in a liquid storage tank shows the amount of vulnerability to which the tank can be subjected. And thus detailed seismic study is required for an affective design. Based on the support conditions, tank can mainly be fixed or flexibly supported on foundation. The numerical model of flexibly supported tank will show the seismic behavior of tank properly as it incorporates fluid structure interactions. Various isolation techniques have also been used to improve the seismic response of the tank. A detailed parametric study of tank with various isolators will be required for better design in future. Tank geometry, depth of liquid in tank, amplitude of ground motion etc. are the different parameters that affects the severity of sloshing and dynamic pressure. Most of the earlier studies focused on sloshing waves based on various excitation. Sloshing height and associated increase in pressure on side walls and roof, ovalling vibration modes, overturning exerting extra pressure along portions of bottom edge of side wall etc. are thus very important to predict the different types of damages caused to the tank.

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