Seismic Analysis of Oil Storage Tanks

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Abstract— Liquid containing tanks (LCTs) are used in water distribution systems and in the industry for storing water, toxic and flammable liquids and are expected to be functional after severe earthquakes. Seismic analysis is performed on numerical model of steel circular vertical ground-situated model tank containing oil. Tanks are assumed to be fixed to a rigid foundation. The responses of cylindrical steel tank are analyzed using Time History Analysis and Modal analysis by means of finite element software package ANSYS. Variation in mode shapes with changing height of liquid fill is observed. A parametric study is conducted by varying the liquid fill height and hence the variations of maximum sloshing wave height, equivalent stress, normal stress, natural frequencies and mode shapes are determined. And it is found that sloshing height increases with increase in liquid height. It also shows that increase in volume of stored liquid leads to a rise in chances of Elephant-foot buckling. However, the diamond wall buckling occurs in all fill condition as the thickness of the shell wall is small.

Key words: Storage Tank, Oil, ANSYS, Sloshing, Diamond Wall Buckling, Elephant Foot Buckling

I. Introduction

All over the world liquid storage tanks have frequently collapsed or been heavily damaged during earthquakes. Damage or collapse of the tanks during these earthquake causes some unwanted events such as shortage of drinking water, uncontrolled fires and spillage of dangerous fluids. For this reason, many theoretical and experimental investigations of the dynamic behavior of different types of liquid storage tanks have been conducted to find out the possible improvements in the design of such tanks to resist earthquake excitation.

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 and purpose of the tank. Based on the shapes it can be circular, rectangular, square, cone-shaped or other shapes. The most common construction materials used are steel and concrete. Concrete tanks can be again classified as cast-in-place, pre-tensioned or post-tensioned. Furthermore, the method of construction also matters. The next classification comes under 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. 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. 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. 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. 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. 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. 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. It has examined the various effects of baffle parameters such as position, dimension and numbers on the non-linear sloshing response. Moslemi, M.R. Kianoush (2012) made a parametric study on dynamic behavior of cylindrical ground-supported tanks. The dynamic behavior of ground supported cylindrical open top water tanks are investigated. 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.

II. Structural Modelling

A circular constant thickness ground supported steel oil storage tank is modelled using ANSYS 17. The elements used are Solid187, Solid186, Target170, Contact174 and Surface154 elements. The tank has an inner diameter of 10000mm and thickness of 10mm. It is 11000mm high, bottom floor is of 10mm thick with a liquid level of 8300mm (75%). The properties of oil and steel is shown in Table I. It is finely meshed. Various boundary conditions are then applied on to the tank. Meshed model of tank is shown in Figure 1.

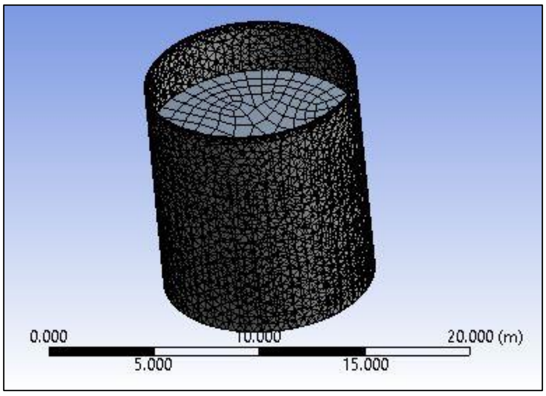


Fig. 1: Meshed Model of tank

	Structure	Fluid
Element	Solid187	Solid186
Density	7850 kg/m^3	890 kg/m^3
Poissons ratio	0.3	-
Youngs Modulus	210 GPa	-
Bulk Modulus	-	1.2 GPa

Table 1: Properties of Structure and Fluid

The inner surface and base of tank is assigned as fluid surface interface for the proper interaction between fluid and solid. Acceleration due to gravity is assigned in the negative Z direction with a value of 9.8066 m/s^2. The base of the tank is fixed to the foundation. Soil structure interaction has to be considered if the tank is flexibly supported to the tank. Hence in this case soil structure interaction can be neglected. Hydrostatic load is also applied on the inner surface of the tank. It increases from 0 value at liquid surface and maximum value comes at the bottom of the surface of tank. The top face of water is assigned as free surface which is necessary for the occurrence of sloshing in the tank. Hence the displacement in both X, Y and Z direction is kept free. The loads and boundary conditions are shown in the figure below.

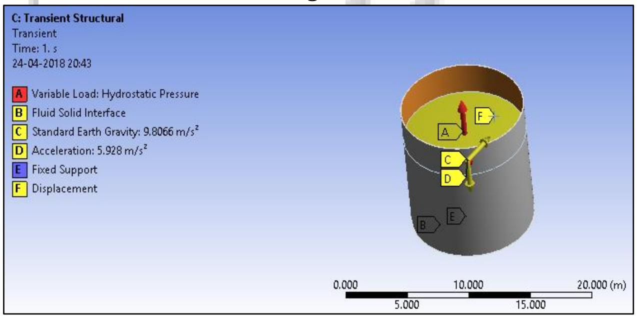


Fig. 2: Loads and Boundary conditions

III. Analysis

Both Time History Analysis and Modal analysis are done to investigate the seismic vulnerability of oil storage tank. For Time History analysis, the accelerogram data taken is IS 1893:2016 Response Spectrum compatible acceleration for soft soil with PGA of 0.9g (Figure 3). The ground motion applied is a 20 sec duration transient acceleration in X direction.

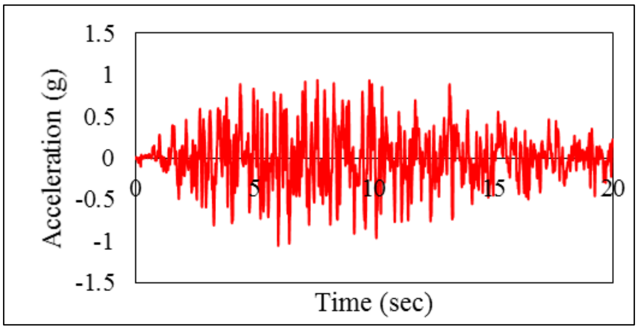


Fig. 3: IS 1893:2016 Response Spectrum compatible acceleration for soft soil

The process of determining the inherent dynamic characteristics of a structure in the forms of natural frequencies, damping factors, and mode shapes is Modal analysis. Modal characteristics of liquid containing structures are affected by the presence of liquid inside the structure. It is analyzed by considering the base of the tank as fixed to the foundation. Modal analysis is then carried out for oil storage tank with liquid in it. Fundamental frequencies and modes are very important in performing the dynamic analysis and understanding the results. Both Time history and Modal analysis are carried out on tank for various liquid fill conditions (empty, 25%, 50%, 75%, and 100% fill conditions).

IV. Results and Discussions

The tank is analyzed for various liquid level conditions and the maximum sloshing height, maximum equivalent stress and maximum normal stress are studied to determine the vulnerability condition. The various liquid level considered for the study are 25%,50%,75% and 100% fill.

A. Sloshing

Sloshing refers to the movement of the free surface of a liquid due to the movement of its container. Figure 4 shows the maximum sloshing in oil storage tank at 25% liquid level for the earthquake loading applied. Figure 4 shows the variation of maximum sloshing wave height at various liquid levels (25% to 100%).

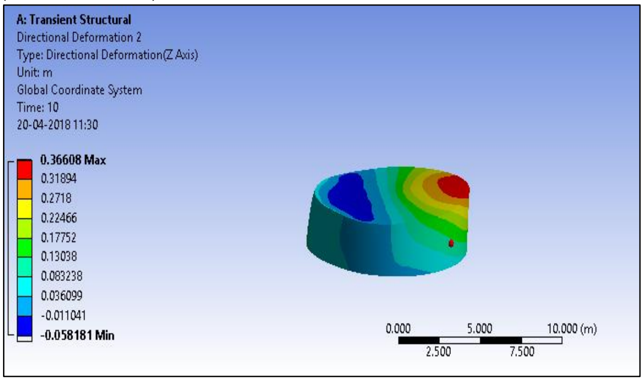


Fig. 4: Sloshing of 25% fills liquid level

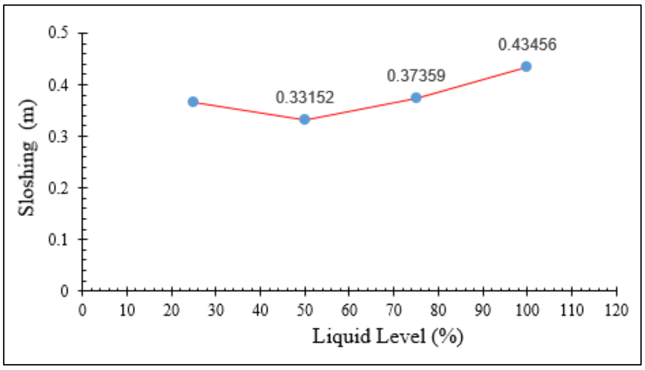


Fig. 4: Sloshing v/s Liquid Level

It can be seen that maximum sloshing occurs at full fill condition (44 cm). Thus the sloshing value helps to find out whether the roof of the tank fails or not. The sloshing lesser for 50% fill condition when compared to 25% fill condition, but increased with further increase in liquid level of tank. Similar effect of increase in sloshing height with respect to the increase in liquid level more than 70% is seen in the studies done by Hossein and Mehrpouya (2012).

B. *Von Mises stress / Equivalent stress*

Equivalent stress is used to know whether a given material will yield or fracture. It is mostly used for ductile materials such as metals. The criterion states that the material will yield if the von Mises stress of a material under load is equal or greater than the yield limit of the same material under simple tension. Thus it corresponds to the diamond wall buckling that happens in the tank. Figure 5 shows the maximum equivalent stress in oil storage tank at liquid levels of 25% for the earthquake loading applied. Figure 6 shows the variation of Equivalent stress at various liquid level (0% to 100%).

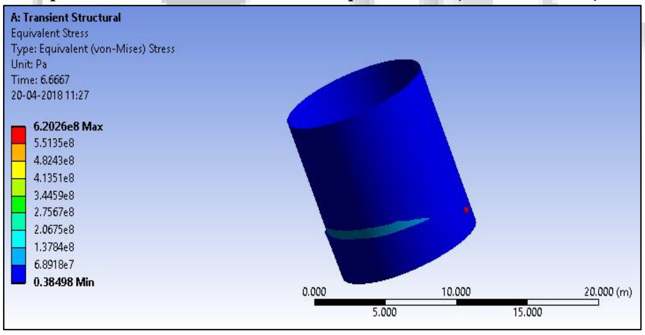


Fig. 5: Equivalent stress of 25% fill condition

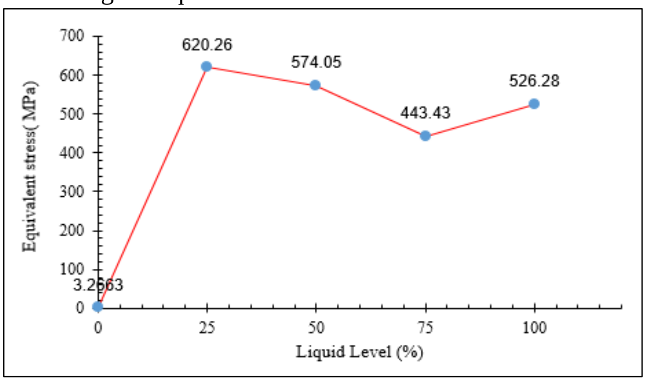


Fig. 6: Equivalent Stress v/s Liquid level

It can be seen that the least value of equivalent stress is for 75% fill condition when compared to all other fill condition, but all values are higher than the minimum yield stress of 250 MPa.

C. *Normal stress*

Tanks are thin shell structures which is subjected to internal pressure due to the liquid inside the tank together with axial compression on the walls. The governing failure mode is frequently buckling under axial compression. The buckling strength can be enhanced due to the internal pressure exerted by the liquid, but it leads to severe local bending near the base. This precipitates an early elastic-plastic buckling failure. This leads to Elephant foot buckling. Figure 7 shows the maximum normal stress in oil storage tank at liquid level of 25% for the earthquake loading applied. Figure 8 shows the variation of Normal stress at various liquid level (0% to 100%).

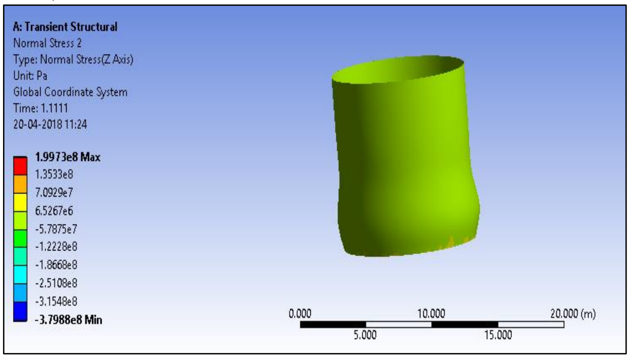


Fig. 7: Normal stress of 25% fill condition

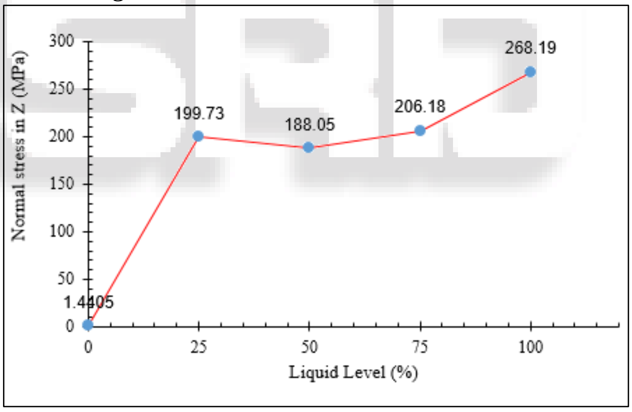
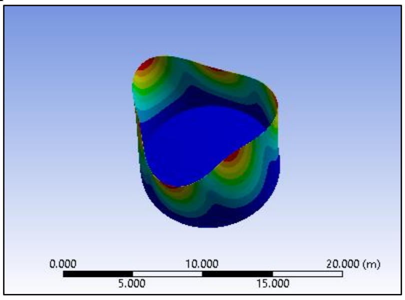


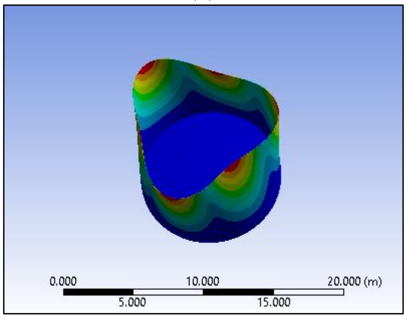
Fig. 8. Normal Stress v/s Liquid level

It can be seen that maximum normal stress occurs at full filled condition (270 MPa). It can be seen that the least value of equivalent stress is for 50% fill condition when compared to all other fill condition. Full filled condition has got the maximum value of normal stress and it is higher than minimum yield stress of the tank. According to studies done by Mohsen et. al (2017), chances for elephant foot buckling increases with increase in volume of stored liquid. Increase in volume of stored liquid leads to a rise in Elephant-foot buckling possibility.

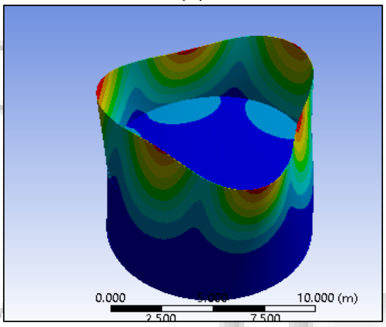
Modal analysis of oil storage tank was carried out in Ansys 17 to study its behavior. It is analyzed by considering the base of the tank is fixed to the foundation. Modal analysis is then carried out for oil storage tank with liquid in it. Fundamental frequencies and modes are very important in performing the dynamic analysis and understanding the results. Modal analysis is carried out on tank for various liquid fill conditions (empty, 25%, 50%, 75%, and 100% fill conditions). Figure 9 shows the fundamental mode shapes of different liquid fill conditions.



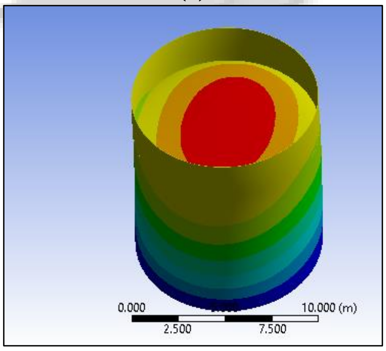
(a)



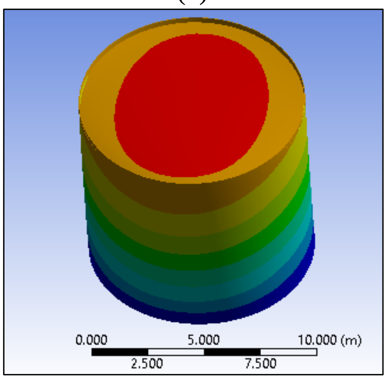
(b)



(c)



(d)



(e)

Fig. 9: Fundamental mode shapes, (a)- empty, (b)- 25% fill, (c)- 50%fill, (d)- 75% fill, (e)- 100% fill

The natural frequencies of oil storage tank are also affected as the fill level is increased. Figure 10 shows the influence of liquid level on natural frequencies at all six modes. All natural frequencies decrease as liquid level is increased, this result shows that the effect of fill level on the vibration characteristics of the tank is the addition of mass.

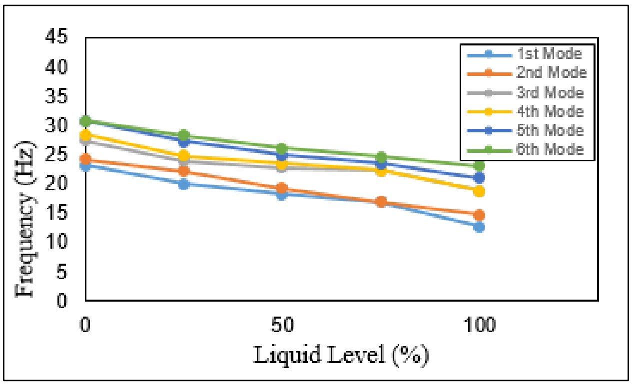


Fig. 10: Effect of fill level on natural frequencies

V. Conclusions

The Time history analysis and modal analysis of oil storage tank is made on five tanks with different filling levels (empty, 25%, 50%, 75%, 100%) and the following conclusions are made.

From the Time history analysis, the various vulnerability conditions such as Maximum Sloshing Wave height, Diamond wall buckling and Elephant foot buckling were found. The parametric study is conducted only by changing the liquid level. Hence the study is limited to a constant H/D ratio. Maximum value of sloshing height comes in oil tank with liquid level of 100% fill condition. Hence the sloshing wave hits the roof which leads to failure. Except 100% fill condition all other sloshing heights does not cause any failure. Similar effect of increase in sloshing height with respect to the increase in liquid level is seen in the studies done by Hossein and Mehrpouya (2012).

Maximum value of Equivalent stress occurs for the tank with 25% fill condition. Minimum value is found in tank with 75% fill condition. Hence we can say that Maximum Equivalent stress of the tank wall for all fill conditions was found to be greater than yield stress, so it is advised to increase thickness of tank wall so as to avoid diamond wall buckling.

Maximum Normal stress occurs in tank with full filled condition which exceeds the yield stress of 250 MPa. Minimum value of normal stress occurred in tank with 25% fill condition. Hence the tank with full filled condition is vulnerable to elephant foot buckling compared to the other fill conditions. Also it is found that increase in volume of stored liquid leads to a rise in Elephant-foot buckling possibility (Moshen et al. (2017)). But according to Parvathy and Jini (2014), it was found that normal stress in 25%, 50% and 100% filling have higher normal stress which exceeds the minimum yield strength. Hence 75% filling is considered safe under seismic effects.

From the Modal analysis, fundamental frequencies and mode shapes where obtained for different fill conditions.

It was found that with the increase in liquid fill heights, the frequency of vibration is decreased.

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