Numerical Analysis of Fire Water Storage Tank under Seismic Loading

Nishanth R¹, Kishok Rai D², Hemkar Sharma³, Rivington Kingston⁴, Davidson Jebaseelan⁵, Christo Michael⁶

¹, ², ³, ⁴School of Mechanical Engineering, VIT Chennai
⁵ Consultant & ASME Authorised Inspector, Chennai, India
⁶Corresponding Author
*E-mail address: nishanth.r2018@vitstudent.ac.in

Abstract. Maintenance and continuously monitoring the condition of above ground storage tanks are significant when the tanks are placed in service. The American Petroleum Institution (API) 653 and other international codes provides the minimum requirements for inspection & maintaining the integrity of tanks during its service. The tank settlement is one of the major threats for tank’s integrity. In this paper, a storage tank is assessed for uniform settlement under various loading condition such as seismic, dead load, static load, corrosion loss of shell plate etc. In the present study, a finite element model is designed with uniform settlement condition and study of its governing hoop stress at shell plate has been carried out under different loading conditions. A fire water storage tank (constructed with IS 2060 GR. B material) and different seismic zones in India are taken for this study. The finite element analysis simulation shows that increase of hoop stress in the bottom shell course due to uniform settlement, the decrease in plate thickness and with different seismic active regions. Moreover, the maximum stresses have been observed at shell bottom course (close to bottom plate).

Keywords: Storage tanks; FE analysis; seismic loading; API 653; Condition monitoring

1. Introduction

Over ground storage tanks are used in a wide variety of industries such as refineries, petrochemical plants, water treatment plants plus a lot more. The structural design of the water storage tank has to make sure it has limited maintenance or service requirements. Most of the normal support configurations include foundation to soil/gravel, ringwall, cement slab or pile with a supporting pile cap. Since they store a large volume of flammable commodities, if the tank fails, major human, ecological and monetary damages are possible. As these tanks are ground-bound and are prone to the movement of tectonic plates, a study of seismic loads is a necessary requirement before a tank fabrication. These tanks tend to suffer the most from damages caused by liquid sloshing due to a long duration of ground motion [1]. These steel tanks are deformed on the base due to edge buckling. Therefore, in rigid tanks, during the horizontal base excitation, a hydrodynamic pressure distribution is developed. Another study created a dynamic model to estimate the liquid reaction in rigid and cylindrical condition forseismically excited tanks [2]. Storage tanks in general, are constructed with different metals based on the contact with different chemicals such as hydrocarbons, water thus, affecting its operational reliability and its service life due to underside corrosion. Contrary to visible parts and accessories, corrosion on the underside is frequently obscured and ignored before leaks occur [3]. Therefore, for this study different plate thicknesses are considered and have been analysed with four different regions of seismic loading. The seismic zones map of India, produced by the Bureau of Indian Standards (IS-2002), was used to determine different loading situations. According to the map, the country is divided into four seismic danger zones, ranging from low (zone II) to very high (zone V), which correspond to Zone D and Zone A respectively [4]. There are no initial settlement readings, so the tank has been constructed with a uniform settlement. The methodologies that have been applied in this paper can be used for different parameters such as varied fluid height and density.

2. Methodology

The model has been created in Solidworks 2020 and has been analysed in Ansys 2019 R3. Assumptions for the study include using hydrostatic pressure instead of fluid-solid interaction, and not constructing a fixed roof; instead, the magnitude of the force is given on the shell's edge.
2.1. Model Specifications

Table 1. The table represents the tank’s specification and its stored fluid properties

| Properties                          | Values                                      |
|-------------------------------------|---------------------------------------------|
| Material of Construction/Code       | IS2062 Gr B/ IS803& API                      |
| Yield strength                      | 650                                         |
| Capacity of Tank                    | 250 Mpa (considered)                        |
| Diameter of Tank                    | 855KL                                       |
| Height of Tank                      | 9 M                                         |
| Tank Material                       | Structural Steel                            |
| Number of Shell                     | 13.5 M                                      |
| Course/thickness                    | 13/ (6mm throughout)                        |
| Storage material type               | Fire water                                   |
| Density of Storage material         | 997 kg/m³                                   |
| Liquid Height (allowable)           | 10.8 M (80% of total height)                |
| Type of Roof                        | Conical fixed roof                          |
| Inspection Code                     | API 653 /API 579                            |

Figure 1. Finite element mesh of the tank

Table 1 shows how the tank was modelled using standard geometry. As a result, the tank was meshed as illustrated in Figure 1, and a mesh convergence study was conducted to determine the needed mesh size. The mesh size was reduced from 1 meter to 50mm and the results converged at 50mm. Thus, the number of elements and nodes can be seen in Table 2.

Table 2. Finite element mesh details

|               |               |
|---------------|---------------|
| Nodes         | 83513         |
| Elements      | 83486         |

In a simulation involving structures of large scale, type of meshing and the size of its elements play an important part in the accuracy of the end results. When directional flow elements are present, the ability to anisotropically tune the mesh makes a huge difference in the ultimate problem size. Hexahedral elements were predominantly used in the study.
2.2. Finite element analysis of the storage tank

For studying seismic and tilting conditions on a storage tank, linear static analysis type of FEA was selected. This was particularly picked, as in our work the analysis holds a linear relationship between applied forces and the displacement of the tanks surface. Moreover, model’s linear stiffness is constant and no non-linear materials are involved in it. Whereas when working sloshing with materials like water, different solvers like non-linear or fluid would be a better choice for the analysis. The maximum allowable stress model was used to analyse the failure, deformation and stress was visualized in the post processing.

For meshing quad elements were used in the shell model which is more accurate for models whose thickness is negligible compared to other dimensions. The model and the settings were validated from [5] in which different larger tanks were studied with diameters ranging from 9.7m-34.93m and height from 7.32m-10.97m with south-eastern Asia earthquake zones and 0–2-degree tilt. For reproducing the real-world scenario an anchored plate with fixed support at the bottom was taken with standard earth gravity in negative Z direction, hydrostatic pressure of water was considered along the inner cylindrical surface that varying with height.

A dead load representing the fixed roof’s weight is calculated according to the dimension and has been initialized. The weight of a circular roof is multiplied by 1.5 to get the weight of a conical roof. So, it is

\[
\text{Dead Load} = \pi r^2 \times \text{thickness} \times \text{density} \times g \times 1.5
\]

\[
= \pi \times 4.5 \times 4.5 \times 0.008 \times 7850 \times 9.8 \times 1.5 = 58730 \text{ N}
\]

The ground motion is given as acceleration in a direction, in step time which varies with different seismic zones which can be seen in Figure 2 [6]. This study used static analysis to determine the maximum magnitude earthquake acceleration over a 0-0.2 second duration.

Seismic Zone: (\(g = 9.8 \text{ m/s}^2\))

- Zone A: 0.25 g – 0.4 g
- Zone B: 0.2 g – 0.25 g
- Zone C: 0.1 g – 0.2 g
- Zone D: 0 g - 0.1 g

This additional load was addressed as a static load with inertia force due to the distributed mass that is delivered to the inner surfaces of the shell due to sloshing of the fluid inside the tanks.

\[
\text{Distributed Mass} = \text{Density} \times \text{Volume} = 830 \times \pi \times 4.5 \times 4.5 \times 13.5 = 712832 \text{ kgs (100% filled)} \quad (2)
\]

3. Results and Discussion

![Stress at 3 mm thickness](image)

**Figure 3.** Stress at 3 mm thickness: (a) Zone A, (b) Zone B, (c) Zone C, (d) Zone D

These images show the equivalent stresses at different regions which can be seen in Figure 3. We observe that the maximum stresses are exceeding the allowable stress that had been calculated earlier. Thus, failure of the tank is imminent in all the cases at 3 mm plate thickness.
Figure 4. Total deformation at 3 mm thickness (a) Zone A, (b) Zone B, (c) Zone C, (d) Zone D

The total deformation values can be seen in Figure 4 with respect to its contour band’s colour. Each Band represents a value and the maximum deformation occurs at the region coloured in red.

| Thickness | Seismic Zone | Maximum Stress (in Mpa) | Total Deformation (in mm) |
|-----------|--------------|-------------------------|--------------------------|
| 6 mm      | Zone A       | 517                     | 0.0049                   |
|           | Zone B       | 304                     | 0.0027                   |
|           | Zone C       | 105                     | 0.0012                   |
|           | Zone D       | 95                      | 0.0019                   |
| 4.5 mm    | Zone A       | 355                     | 0.0037                   |
|           | Zone B       | 139                     | 0.0036                   |
|           | Zone C       | 333                     | 0.0035                   |
|           | Zone D       | 124                     | 0.0035                   |
| 3 mm      | Zone A       | 237                     | 0.0086                   |
|           | Zone B       | 231                     | 0.0055                   |
|           | Zone C       | 203                     | 0.0045                   |
|           | Zone D       | 196                     | 0.0039                   |

Figure 5. Maximum stress and deformation across various seismic zones

From the following analysis and the data derived from it, a tabular column is made depicting the Maximum Stress (in Mpa), Maximum Total Deformation (in mm) for various thicknesses and seismic zones which can be seen in Table 5. Each thickness is analysed with respect to all the four seismic zones mentioned in Figure 2.

From the figure 6, the data points are plotted with Maximum Stress (in Mpa) in x axis and Plate thickness (in mm) in y axis.

Figure 6. The maximum stresses across various plate thickness for various seismic zones

From the graph in Figure 6 the following can be observed.
In seismic zone A the value of maximum stress increases slowly from 117 at 6 mm to 155 at 4.5 mm. After that a sudden climb in Maximum stress is found for a smaller decrease in shell thickness. At around 4.3 mm shell thickness the maximum stress exceeds the maximum allowable stress. The highest value of 237 MPa is recorded in this Zone.

In seismic zone B the value of maximum stress increases at a slower rate from 104 at 6 mm to 139 at 4.5 mm. After that a sudden climb in Maximum stress is found for a smaller decrease in shell thickness. At around 4 mm shell thickness the maximum stress exceeds the maximum allowable stress.

In seismic zone C the value of maximum stress increases at a slow pace from 101 at 6 mm to 133 at 4.5 mm. After that a sudden increase in Maximum stress is found for a smaller decrease in shell thickness. At around 3.8 mm shell thickness the maximum stress exceeds the maximum allowable stress.

In seismic zone D the value of maximum stress increases at a very slow rate compared to other zones from 94 at 6 mm to 124 at 4.5 mm. After that a sudden increase in Maximum stress is found for a smaller decrease in shell thickness. At around 3.5 mm shell thickness the maximum stress exceeds the maximum allowable stress. This records all the lowest values of Maximum stresses for the respective thickness.

The vertical line in the graph which is shown in Figure 6, depicts the calculated maximum allowable stress (166 Mpa). All the values obtained from the stipulated conditions are defined as data points in a line graph, where any value which lies beyond the above said safety line or line of maximum allowable stress, a critical failure can be expected in the structure of the tank.

![Figure 6. Calculated maximum allowable stress](image-url)

**Figure 6.** Calculated maximum allowable stress

The total deformation curve is represented in the Figure 7. Zone A has the highest recorded value of deformation of around 0.0086 meter (8.6 mm) at a shell thickness of 3.5 mm at Zone A. The second highest value is at a shell plate thickness of 4.5 mm at seismic Zone A and it is around 0.0057 m. The lowest value found in the simulation occurs at shell plate thickness of 6 mm as expected and the value is 0.0019 m. For a particular seismic zone as the shell plate thickness decreases the total deformation value increases. In a particular shell plate thickness, the value of total deformation decreases as seismic loading decreases across the zones. The type of trend in slope observed from this data is very similar as to that of Figure 6.

**Figure 7.** Total deformation across various plate thicknesses for various seismic zones

![Figure 7. Total deformation curve](image-url)

The total deformation curve is represented in the Figure 7. Zone A has the highest recorded value of deformation of around 0.0086 meter (8.6 mm) at a shell thickness of 3.5 mm at Zone A. The second highest value is at a shell plate thickness of 4.5 mm at seismic Zone A and it is around 0.0057 m. The lowest value found in the simulation occurs at shell plate thickness of 6 mm as expected and the value is 0.0019 m. For a particular seismic zone as the shell plate thickness decreases the total deformation value increases. In a particular shell plate thickness, the value of total deformation decreases as seismic loading decreases across the zones. The type of trend in slope observed from this data is very similar as to that of Figure 6.

**4. Conclusion**

In this study, 12 distinct numerical studies on a tank with a capacity of 855 Kilolitres was undertaken. Due to the decrease in plate thickness and the rise in seismic load, the simulation reveals an increase in hoop stress. The highest stresses were discovered near the tank’s annular connection. It is a major source of concern and are suspected to be the host of maximum stress. The real validation was carried out in Itrasi’s 855KL tank. In terms of homogeneous settlement, parameters such as plate thickness and seismic stresses have an impact on the outcomes. Planar settlements can be used to further investigate this research. Any
other additional equipment attached to the tank is not included in this study and they need to have separate safe operating conditions.

References:
[1] VakilaadSarabi, A. and M. Miyajima. Study of the Sloshing of Water Reservoirs and Tanks due to Long Period and Long Duration Seismic Motions. in PROCEEDINGS OF THE FIFTEENTH WORLD CONFERENCE ON EARTHQUAKE ENGINEERING. 2012.

[2] Housner, G.W., Dynamic pressures on accelerated fluid containers. Bulletin of the Seismological Society of America, 1957. 47(1): p. 15-35 DOI: 10.1785/bssa0470010015.

[3] Okokoyo, P., Underside Corrosion of above Ground Storage Tanks (ASTs). Journal of Applied Sciences and Environmental Management (ISSN: 1119-8362) Vol 9 Num 1, 2005.

[4] Verma, M., R.J. Singh, and B.K. Bansal, Soft sediments and damage pattern: a few case studies from large Indian earthquakes vis-a-vis seismic risk evaluation. Natural Hazards, 2014. 74(3): p. 1829-1851 DOI: 10.1007/s11069-014-1283-4.

[5] Wisnugroho, J. and Sutomo, Numerical Study of Oil Storage Tanks during Planar Settlement. Applied Mechanics and Materials, 2018. 878: p. 95-103 DOI: 10.4028/www.scietific.net/AMM.878.95.

[6] Mohanty, A. An Overview of Seismic Zonation Studies in India. in Indian Geotechnical Conference. 2010.