NUMERICAL ANALYSIS OF SEISMIC RESPONSE OF STEEL CYLINDRICAL LNG STORAGE TANKS

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Numerical analysis of the seismic response of steel cylindrical LNG (liquified natural gas) storage tanks is essential to designing such structures to ensure their safety and structural integrity during earthquake events. The seismic analysis involves the assessment of the tank's response to ground motion and evaluating its structural performance under seismic loads. The LNG storage tanks' seismic behavior is rarely reported when the tank is subjected to strong earthquakes. This paper evaluates the vibration characteristic (modal analysis) and the seismic response analysis, e.g., time history response, displacement vs. time, and distribution of the maximum Von-Mises stresses of the perfect cylindrical storage tanks. This paper uses the finite element analysis (FEA) technique using ABAQUS CAE-2019 to evaluate the seismic capacity in peak ground acceleration (PGA). Three perfect cylindrical tanks (PCT) have been considered first for modal analysis, with two having high-yielding strength and the rest with low-yielding strength. Then El-Centro 1940 seismic waves are applied as a horizontal ground motion at the fixed base of the tanks. Finally, the results from the modal analysis regarding the first natural frequency of the tank models are compared with those obtained from experiments. The result's comparisons illustrate that the numerical simulation agrees well with the experimental test results.

Keywords: Liquified natural gas, Vibration characteristic, Finite element analysis, ABAQUS, Local buckling.

1 INTRODUCTION

The liquified natural gas (LNG) storage tank mainly constructs with an external concrete tank, an inner steel tank for storing LNG, and some insulation materials between the tanks. Due to the leakage problem and safe operation of such storage tanks, the proper seismic analysis and design for these tanks have become the primary focus for researchers and rate attention in the design of LNG storage tanks. With the recent development and advancement in the economy, the demand for energy and consumption of LNG worldwide is increasing daily. It was noted in 2020 that 487.9 billion cubic meters of LNG were consumed (Chen et al. 2022). So far, many researchers have studied the seismic behavior of storage tanks through their experimental and numerical simulations (Mamaghan and Roopkumdee 2021). Veletsos and Tang (1986, 1987) presented a seismic design method and the liquid’s effects on the anchored vertical storage tank. Clubley (2014) presented an experimental and numerical approach to evaluate the non-linear response of the shell structure (Aluminum shell) having different liquid levels subjected to long-term loading. Mittal et al. (2014) used commercial ABAQUS software to use the finite element (FE) technique. They studied the various parameters like shear stresses, storage tank response filled with liquid, liquid sloshing depth, the height of liquid filled, boundary conditions, and wall thickness of the storage tank. Jennings (1971) prepared a report on the damage to different storage tanks after the San Fernando
Earthquake. Berz (1988) reported all the disasters (natural), including the different seismic events between 1960-1987. He concluded that the earthquake’s damage is the most prominent among all other disasters. Furthermore, detailed investigations about the different damage caused by the seismic events from 1933-1983 (earthquake) in the storage tanks and other refineries’ oil reservoirs were made by Nielsen and Kiremidjian (1986). To evaluate the effects of different parameters on the seismic buckling response of cylindrical storage tanks, Moslemi and Kianoush (2012) presented an FEA using the commercial software ANSYS. The interaction effects of the radius-to-thickness ratio, $R/t$, and height-to-radius ratio, $H/R$, of the cylindrical tanks on the dynamic buckling are investigated, and estimated design equations are proposed by Roopkumdee and Mamaghani (2021).

2 MODEL DESCRIPTION

2.1 Geometric Configurations and Mesh Convergence Studies

As given in Figure 1(a), the cylindrical storage tank models used during modal analysis are the circular cylindrical tank with $H = 640$ mm, $R = 160$ mm, and the thickness of the cylindrical tank has taken as 0.8 mm. The $H/R$ and $R/t$ ratio is taken as 4 and 200 respectively. In this modal analysis, three perfect cylindrical tanks (PCT) have been taken, e.g., PCT-A, PCT-B, and PCT-C. The first two tanks have a relatively high yielding strength of 250 MPa, and the other one with low yielding strength, e.g., 129 MPa. The density and poison ratio of the mild steel is taken as 7850 kg/m$^3$ and 0.3, respectively. Furthermore, the weight placed on the top of the storage tank is considerably more significant than the self-weight of the tank, and hence it can be considered as a single degree of freedom (SDF) system. The geometric configuration with the fixed base has been introduced in the boundary condition (B.C.) step, as shown in Figure 1.

![Figure 1](image_url)

Figure 1. (a) Tank geometry, (b) boundary conditions, (c) meshing of a cylindrical tank.

The perfect storage tank models are considered with different mesh sizes such as 5, 10, 15, 20, and 25 for the total number of elements and their effect on vibration characteristics or first natural frequency of the cylindrical tanks. Based on the mesh convergence study, the 5 mm mesh size with a total of 6464 elements is more suitable and satisfactory for close and accurate results regarding the natural frequency of the model specimens. Finally, for each storage tank, the 5 mm mesh size shown in Figure 1(c) is considered an optimum mesh size, and the natural frequency is recorded for all perfect cylindrical storage tanks.

3 MODEL ANALYSIS

3.1 Vibration Characteristics of the Cylindrical Tank

The model analysis for the cylindrical storage tanks has been carried out to calculate the storage tanks' natural frequency and mode shapes. In the model analysis, the output is the first natural
frequency cycle/time or Hz shown in Table 1 and the first mode shape of the perfect cylindrical storage tank A and C, as given below in Figures 2(a) and (b).

![Figure 2. First mode shape, (a) PCT-A, (b) PCT-C.](image)

<table>
<thead>
<tr>
<th>Tank Modal</th>
<th>First Natural Frequency-FEA</th>
<th>First Natural Frequency-Experimental Results</th>
<th>Circumferential Waves-FEA</th>
<th>Circumferential Waves-Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCT-A</td>
<td>21.92</td>
<td>20.9</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>PCT-B</td>
<td>21.92</td>
<td>21.0</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>PCT-C</td>
<td>20.00</td>
<td>18.5</td>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>

4 COMPARISON WITH TEST RESULTS

The comparison in Table 1 shows that the FEA and experimental values are close enough to each other, which proves a good agreement between them. A slight difference in the experimental values is mainly because of the imperfect nature of the storage tank. In FE analysis, all the tanks are considered perfect models. At the same time, during the experimental test, the imperfection was taken as approximately within the magnitude of the wall thickness of the storage tank. Furthermore, the slight difference in the experimental observed natural frequency is due to the difference in the center of gravity of the lumped mass/weight at the top of the storage tank (Fujita et al. 1991).

5 LINEAR SEISMIC ANALYSIS

Time-dependent loading, a linear/elastic dynamic model, has been introduced in ABAQUS. The dynamic modal analysis also considers the lumped mass on the top of the storage tank and the damping effect. Based on the literature, all the tank models are considered to have a single degree of freedom in the horizontal direction. The Rayleigh damping with the critical damping ratio of 3% has been used for the modal analysis. The seismic analysis of the tank models is carried out by employing the El-Centro seismic record up to a maximum of 31.18 seconds in the horizontal direction. The numerical value for the acceleration and time has been taken in terms of g (m/sec²) and sec, respectively. The peak ground acceleration (PGA) from the accelerogram is 0.319 at 2.02 seconds. Figures 3(a) and (b) represent the critical point concerning the maximum acceleration and displacement of the storage tank.

The time history response of tank A at the N-2415 shows that the maximum peak ground acceleration (PGA) is about 0.562g at 2.49 sec, as shown in Figure 4. Similarly, the displacement vs time response for tank A is shown in Figure 5.
From the output accelerogram data, the acceleration and displacement vs time response of tank C are shown in Figure 7 and Figure 8 respectively and the acceleration response shows a maximum PGA of about 0.3 g at a time of 2.45 sec. The critical location, which shows the maximum mises stress (N/mm²) at the base side of storage tank A, is greater than tank C as shown in Figure 6. This is because of the low-yielding strength of tank C. Generally, it can be seen that the stress
distribution is greater at the bottom side mainly due to the applied ground motion in the horizontal direction and its decreases along the height of the tank as shown in Figure 9.

![Figure 6. (a) Location of maximum acceleration PCT-C, (b) max. displacement PCT-C.](image)

![Figure 7. Time history response of tank-C.](image)

![Figure 8. Displacement vs. time response of PCT-C.](image)
6 CONCLUSIONS

In this study, the modal analysis to evaluate the vibration characteristics of the empty storage tanks and seismic response analysis, e.g., time history response, displacement vs. time response, and the distribution of the stresses at crucial locations for three perfect cylindrical storage tanks has been conducted by using commercial software ABAQUS. Linear elastic seismic analysis has been carried out to evaluate the time history response, displacement vs. time, and the tanks’ maximum mises stress location. The study shows that the experiment results follow the results of the numerically predicted value of all the tanks' natural frequency (vibration characteristic). Based on this simulation, it has been concluded that the adopted finite element modeling is reliable and can be used for seismic performance evaluation of cylindrical storage tanks.

References