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Numerical assessment and seismic performance evaluation of thin-walled cylindrical liquid-filled steel storage tanks supported on rigid soil

Shafqat Ullah[1], Iraj H. P. Mamaghani[2]

Abstract
The seismic response of liquid storage tanks differs significantly from that of conventional structures, not only due to the hydrodynamic effects acting on the tank shell but also because of various sources of nonlinear behavior. These include the buckling of the tank shell, large amplitude nonlinear sloshing, nonlinear soil structure interaction (SSI), material yielding, plastic rotation of the base plate, and the successive contact and separation between the tank base and the soil. To assess the earthquake response of such structures, numerical methods are essential, as they provide an efficient means of accurately capturing all these nonlinearities within a single model. This research primarily focused on the seismic behavior of liquid-containing tall tank subjected to three different real-world earthquake ground motions. The main objectives are to evaluate the stresses distribution, deformation response, time history response and the total hydrodynamic pressure response. The study utilized finite element (FE) based numerical model using ABAQUS software by employing least computational approach called coupled-acoustic structure (CAS) interaction to capture the interaction between the tank inner surface and liquid domain. The findings reveal that the tank subjected to static loading experience a small deformation and stresses near the tank bottom. Furthermore, tank under different input seismic excitations, deformation response, von-mises, and circumferential stresses are significantly changed compared to static loading. The time history response for each case shows that tank experience a maximum peak acceleration at the top node of the tank compared to middle and bottom node. It was found that the tank subjected to earthquake of PGA 0.49g experienced maximum peak acceleration response at the top node and total hydrodynamic pressure near the bottom of the tank. These responses are reduced significantly when the tank subjected to earthquake of PGA 0.23g as well as 0.39g.

Keywords: Local buckling, Thin-walled cylindrical tanks, Fluid-structure interaction (FSI), Time history response, hydrodynamic pressure, Finite element analysis (FEA), ABAQUS.

[1] PhD Student, University of North Dakota, USA, <shafqat.ullah@und.edu>
[2] Associate Professor, University of North Dakota, USA, <iraj.mamaghani@und.edu>

1. Introduction

Globally, liquefied natural gas (LNG) is increasingly recognized for its advantages over other fossil fuels, particularly its ease of transport and lower carbon dioxide (CO_2) emissions. According to the U.S. Energy Information Administration (EIA), worldwide energy consumption is projected to increase by 48% between 2012 and 2040. Natural gas can be transported via pipelines in its gaseous state or as LNG, which occupies approximately 600 times less volume when liquefied at cryogenic temperatures of -160 °C. This efficiency in storage and transport makes LNG a key player in meeting future energy needs. Due to this increasing demand for LNG as a cleaner energy source has prompted the construction of large-scale LNG storage facilities with capacities ranging from 160,000-225,000 m^3 (Sharari et al. 2022). These storage tanks, which are designed to hold natural gas at cryogenic temperatures, are vital components of the energy infrastructure across various sectors. Among the various types of storage structures, thin-walled cylindrical steel tanks are widely used due to their efficient design and capacity to withstand the challenging operational conditions associated with LNG. However, these tanks are vulnerable to seismic events, which can pose significant risks to their structural integrity and safety. The most dominant earthquake-induced damages are elephant's foot (Elastic-plastic) buckling, diamond shaped (Elastic) buckling, and failure of base-plate connection due to uplifting as shown in Figure 1 (a-c). Therefore, an adequate seismic design to ensure overall safety, and reliability of LNG storage facilities in seismically active regions is of great importance for structural engineers.

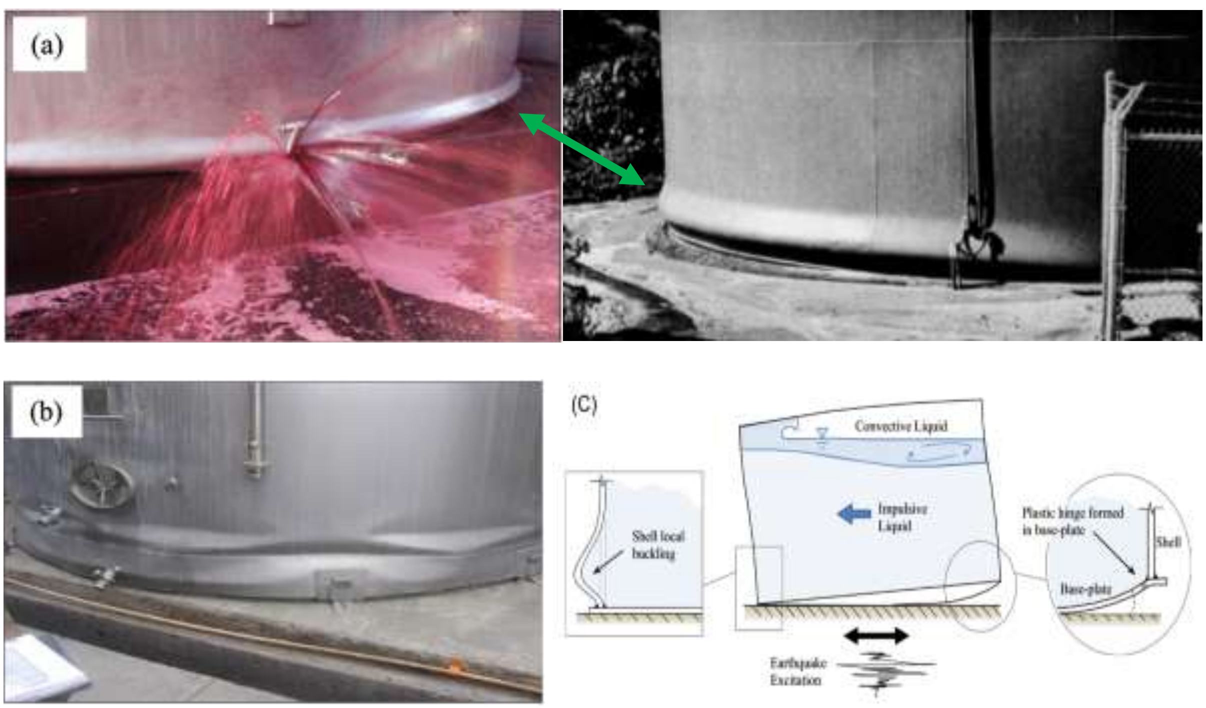


Figure 1. (a): Fracture in the Tank wall due to inelastic deformation - Elephant's foot buckling, (b): Diamond shaped (Elastic) buckling, (c): Separation of base-plate - Uplifting mechanism

Over the past two decades, numerous researchers have focused on evaluating the dynamic behavior of liquid-filled storage tanks through experimental, numerical, and analytical approaches. Early investigations such as those by Housner (1957), primarily focused on the dynamic behavior of liquid-filled storage tanks subjected to seismic excitations. The author introduced a simplified mechanical model that separates the liquid mass into two components: impulsive mass and convective mass. The impulsive mass moves rigidly with the tank walls, generating hydrodynamic impulsive pressure that can create an overturning moment at the base of the storage tank. In contrast, the convective mass moves independently and over a longer period, leading to hydrodynamic convective pressure. The convective pressure component can result in sloshing phenomena, potentially causing severe damage to the upper portion of the tank. Significant progress was accomplished by studying the damage to tanks during the 1964 Alaska and the 1971 San Fernando earthquake. Several researchers have contributed their efforts by introducing different analytical approaches for evaluating the dynamic behavior of rigid and flexible liquid-filled storage tanks. Wozniak and Mitchell in 1978 generalized Housner's model for short and slender tanks, while Veletsos and Yang 1977 adopted a different approach to create a similar mechanical model for circular rigid tanks. Later, Haroun and Housner 1981 developed mechanical models specifically for flexible tanks. Malhotra et al. 2000 further simplified Veletsos's flexible tank model. Figure 2 illustrates comparisons of different parameters of flexible and rigid liquid-filled storage tanks.

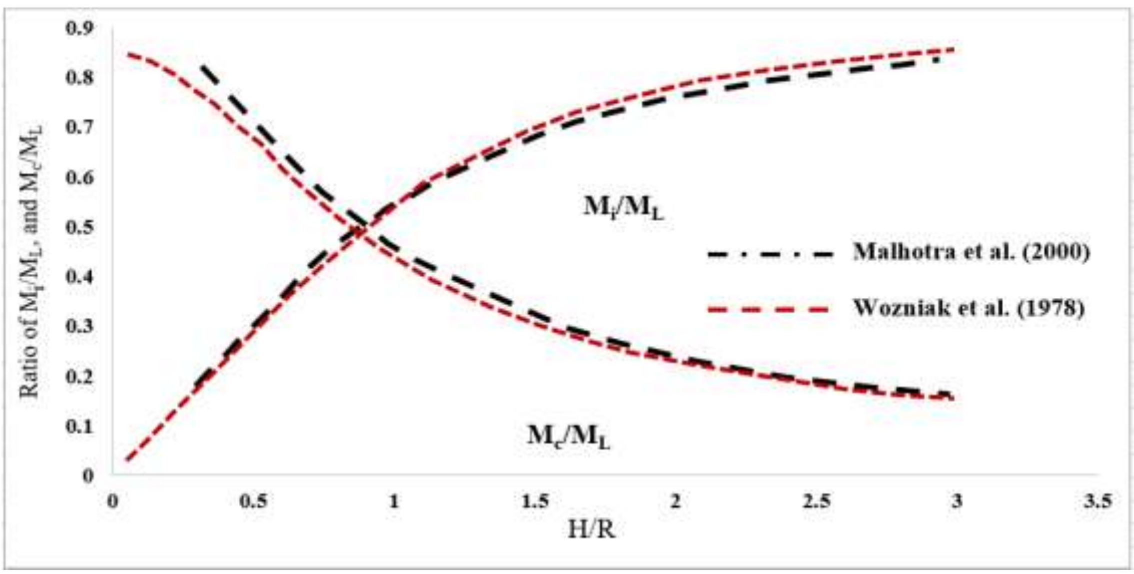


Figure 2. Variation of various design parameters with respect to *H/R* ratio

1.1 Fluid-Structure Interaction (FSI)

A fluid storage tank operates as a coupled system, with its dynamic behavior governed by the interaction between the motions of the fluid and the tank's walls and bottom. The critical aspect of investigating the dynamic responses of fluid storage tanks lies in analyzing fluid–structure interaction (FSI), a complex phenomenon that has been addressed by numerous researchers using various approaches. The fluid domain is typically described by fluid dynamics equations, including Navier–Stokes, Laplace, and Bernoulli equations, which are used to determine the hydrodynamic pressure distribution on the tank walls. Recently, the application of acoustic wave theory, through the Helmholtz equation, has been considered for studying seismically induced sloshing and the hydrodynamic behavior of fluid storage tanks (Rawat et al. 2019). Figure 3 shows the interaction between the inner liquid and tank structure.

In addition to analytical approaches, numerous researchers have employed experimental and numerical techniques to evaluate the dynamic behavior of rigid as well as flexible liquid-filled steel storage tanks, considering FSI. Early investigations into the seismic effects on rigid tanks resting on rigid foundations were conducted by Housner in 1963. Veletsos and Yang (1977) analyzed the seismic behavior of a cylindrical liquid storage tank, modeling it as a cantilever beam. The authors treated the tank and the liquid as a single-degree-of-freedom system, focusing on the tank's lateral displacement at the free surface. To account for the liquid's inertial effects, the researchers employed the added mass approach, incorporating part of the fluid mass into the

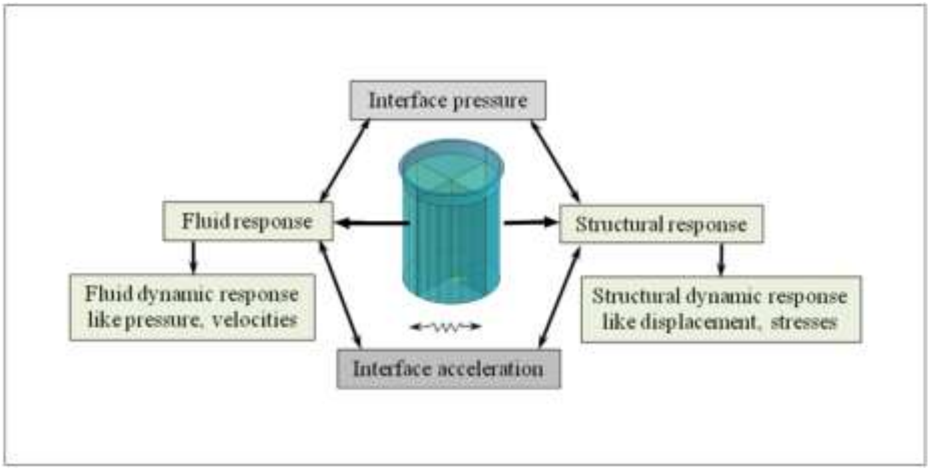


Figure 3. Fluid-structure interaction in liquid-filled tank

structural mass of the tank. Consequently, their study concentrated solely on the impulsive component. Additionally, Yang (1976) examined the behavior of cylindrical storage tanks and found that the impulsive pressure was lower for rigid walls compared to flexible ones. Maekawa and Fujita (2010) employed a detailed 3D finite element method (FEM) to investigate the dynamic buckling behavior of storage tanks subjected to earthquake loading. Their study examined the effects of tank geometry and mesh sensitivity on the dynamic buckling response. Similarly, Virella et al. (2008) explored the nonlinear static buckling behavior of anchored steel storage tanks under seismic loading. The authors presented three different cylindrical tank models, determining the corresponding buckling capacity in terms of critical peak ground acceleration (PGA). The study concluded that for all cases considered, the proposed procedure yielded somewhat lower critical PGA values for the first elastic buckling compared to dynamic buckling results. Ullah and Mamaghani (2024) evaluated the buckling behavior of storage tank under static loading. Ormeño et al. (2019) experimentally investigated the effects of base flexibility on seismic response of liquid-filled storage tank. The authors concluded that flexibility of tank base greatly influences the dynamic behavior of the tank compared to rigid base condition. Consequently, Zhao et al. (2020) evaluated the seismic response of LNG storage tank, and the effects of different liquid levels are investigated. Compagnoni and Curadelli (2018) presented an experimental and numerical approach to study the dynamic response of circular steel liquid-filled tank subjected to seismic excitations. The authors considered three different broad and slender steel tanks, and the corresponding sloshing wave height, base shear and overturning moment were calculated. Goudarzi and Danesh (2016) numerically investigated the hydrodynamic damping effects of vertical baffles in full-scale rectangular liquid tanks. Maleki and Ziyaeifar (2007) examined the impact of baffles in reducing earthquake responses in seismically isolated cylindrical liquid storage tanks. Hosseini et al. (2017) proposed a passive control technique using a suspended annular baffle to reduce the maximum sloshing height (MSH) in floating roof liquid storage tanks during earthquakes, and its effectiveness was validated through various shake table tests on a small model tank. in recent year Ullah et al. (2024) investigated the seismic behavior of flexible liquid filled storage tank subjected to different input PGAs. The authors presented detailed 3D FEA to evaluated the time history response, stress distributions, and the total hydrodynamic pressure of the given liquid-filled storage Tank. Ullah and Mamaghani (2024) investigated the seismic performance of three different (tall, moderate broad and broad) liquid-filled storage tanks subjected to seismic excitations. The authors investigated the effects of liquid sloshing near the top surface of the tank and the corresponding hydrodynamic pressure under input seismic excitations.

1.2 Soil Structure Interaction (SSI)

The seismic response of storage tanks is a critical area of study, particularly in the context of Soil-Structure Interaction (SSI). As these tanks often contain hazardous materials, understanding their behavior during seismic events is essential for ensuring safety and minimizing environmental risks. SSI plays a pivotal role in influencing how seismic waves affect both the soil and the tank structure, leading to complex interactions that can amplify or mitigate the overall response. Several experimental and analytical investigations have underscored the importance of SSI, especially for large structures like tall buildings, bridges, and liquid storage tanks (Halabian et al. 2002, Stewart et al. 1999, and Yu et al. 2021). Analytical approaches have primarily employed the Finite Element Method (FEM) to evaluate overall behavior, alongside Nonlinear Static Pushover Analysis (NSPA) to analyze uplift and stress redistribution (Bakalis and Karamanos 2021). Additionally, FEM has been utilized to estimate critical ground accelerations for liquid storage tanks by integrating NSPA with the Capacity Spectrum Method (CSM) (Virella et al. 2008, and Moreno et al. 2023). FEM has also been employed to analyze tanks directly supported on the ground, revealing the influence of soil flexibility on the axial compressive stress of the tank wall (Bakhshi 2008). Additionally, simplified numerical models have been developed, demonstrating that soil-structure interaction significantly affects the seismic response of liquid storage tanks (Jaramillo et al. 2022).

Hussein et al. (2021) investigated the hydrodynamic pressure effects on the tank considering SSI. Their findings demonstrate that the base flexibility and soil types have significant influence on the base displacement and shear stresses at the tank bottom. Other researchers have evaluated the dynamic behavior of storage tanks subjected to ground motions (Xin et al. 2021). The authors compared the effects of soil interaction with a tank model that did not incorporate soil-structure interaction. Recent investigations have examined the elephant’s foot buckling in both anchored and unanchored liquid-filled storage tanks, assessing the impact of three different soil conditions (Ulloa-Rojas et al. 2024). The authors employed the capacity spectrum approach to identify the critical peak ground acceleration (PGA) that triggers buckling in the tank wall. Hernandez et al. (2018) conducted shake table test to investigate the nonlinear soil-structure-fluid interaction of thin-walled liquid-filled steel storage tank subjected to seismic excitations. The authors investigated the effects of base fixity, flexibility and the aspect ratio on the overall tank response. Studies such as (Haroun and Temraz 1992, Veletsos et al. 1990, and Veletsos et al. 1992) have reported that SSI can be beneficial to the seismic response of tanks, as both hoop and axial stresses in the tank wall are reduced compared to when the tank is supported on a rigid base. This is because the inclusion of soil flexibility lowers the natural frequencies of the tank-liquid system. Larkin (2008) noted that the effects of SSI depend on both the soil and tank properties, with a particular emphasis on changes to the fundamental frequency of the soil-tank-liquid system. Hernandez-Hernandez et al. (2018, and 2019) experimentally observed that SSI can either increase or decrease the tank's response, depending on the alignment between the dominant frequency of the seismic excitation and the first natural frequency of the soil-tank-liquid system.

Based on the earlier analytical investigations, Provisions on SSI are included in ASCE 7, NZSEE, and Eurocode 8. Soil flexibility increases the impulsive time period and enhances radiation damping, which contributes to the overall increase in the total damping of the structure. ASCE 7, NZSEE, and Eurocode 8 provide expressions for the impulsive time period, accounting for soil flexibility, along with formulas for the equivalent damping, which includes the radial damping of the soil.

To summarize the above discussions, SSI has significant influence on seismic response of liquid-filled storage tanks. Despite the above investigations, there is still needs of understanding the hydrodynamic behavior of large LNG cylindrical tanks resting on different soil profile, nature of the soil, effects of anchored and unanchored base conditions. Detailed FEM approaches needs to be performed to examine the variation of the base shear, overturning moment and nonlinear sloshing behavior of the liquid in cylindrical steel tanks subjected to real-world earthquake loading. This study focuses on the seismic behavior of tall tank supported by the rigid soil subjected to three different real-world ground motions. The parameters including deformation response, stresses distribution, time history response and total hydrodynamic pressure response will be evaluated. The study will use advanced numerical approaches, such as coupled acoustic-structure (CAS) interaction to accurately capture the real behavior of the tank structure under seismic conditions.

2. Finite Element Modeling (FEM) Approach

Finite element analysis (FEA) with the commercial software ABAQUS is utilized to evaluate the dynamic buckling response of liquid-filled cylindrical steel tanks supported on rigid soil. This study examines the impact of seismic excitations on the buckling behavior of cylindrical steel tanks. The fluid-structure interaction (FSI) between the liquid and the tank is modeled using the coupled acoustic-structure (CAS) interaction approach. The CAS method is favored for its simplicity and effectiveness in numerical simulations. It assumes no material flow, which prevents mesh distortion and simplifies the computational model. Additionally, the acoustic element in the CAS approach has only pressure degrees of freedom at each node, greatly reducing the computational time needed for the analysis. The governing equation for acoustic waves is based on the independent variable acoustic pressure as expressed in Equation 1.

$$\frac{\partial^2 P}{\sigma t^2} - c^2 \nabla^2 P = 0 \tag{1}$$

In the above expression, the *c* is the speed of sound in the given liquid and can be estimated using the expression shown in Equation 2.

$$c = \sqrt{\frac{k}{\rho_L}} \tag{2}$$

In the equation (2), the k and ρ_L shows the bulk modulus and mass density of the corresponding liquid, respectively. The interaction between the tank wall and the acoustic liquid is modeled using a surface-based tie constraint, ensuring that both surfaces stay in contact throughout the simulation. This tie constraint enforces equal pressure and displacement at each node on the acoustic liquid surface and the corresponding node on the tank surface closest to it. The details of loading protocol, boundary condition (BCs) and meshing are discussed in section 3.2.

3.1 Geometry and Material Description

This study investigates a tall liquid-filled storage tank supported by rigid soil and subjected to lateral seismic excitations. The detailed geometric properties of the tank, including height (H), diameter (D), thickness (t), height-to-diameter, and diameter-to-thickness ratio, roof thickness (t_r), and freeboard height (H_f), as well as the material properties of the steel, such as modulus of elasticity, plastic modulus, yield stress, ultimate stress, and poison's ratio, are summarized in Tables 1 through Table 3. Carbon structural steel A36 is used for the storage tank, and the bilinear stress-strain relationship for this steel material is shown in Figure 4.

Table 1. Geometric properties of the proposed Tank model

Geometric properties						
Height (H) (m)	Diameter (D) (m)	Thickness (t) (m)	H/D	D/t	Freeboard height (H_f) (m)	Roof thickness (t_r) m
21.96	14.64	0.015	1.5	976	1.00	0.011

Table 2. Material properties of the Tank model

Young modulus (GPa)	Plastic modulus (GPa)	Yield stress (MPa)	Ultimate strength (MPa)	Density (ρ) (kg/m^3)	(v)
206.70	3.38	250	400	7840	0.30

v = Poison's ratio of the given steel material

Table 3. Properties of Soil and Acoustic domain (Liquid)

Soil domain				Acoustic medium	
Density (ρ) (kg/m^3)	Shear wave velocity (C_s^{soil}) (m/s)	Elasticity (E) (MPa)	Poison's ratio (v)	Bulk modulus (MPa)	Density (ρ) (kg/m^3)
2400	6000	200	0.33	2150	1000

The components including the Tank side view, Tank top side (roof) and the assembly of Tank wall and liquid domain is illustrated in Figure 5(a), (b), and (c), respectively.

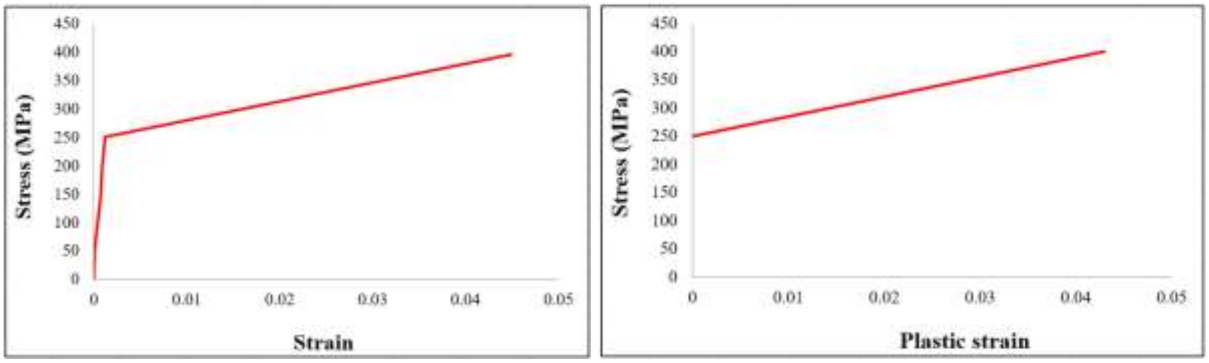
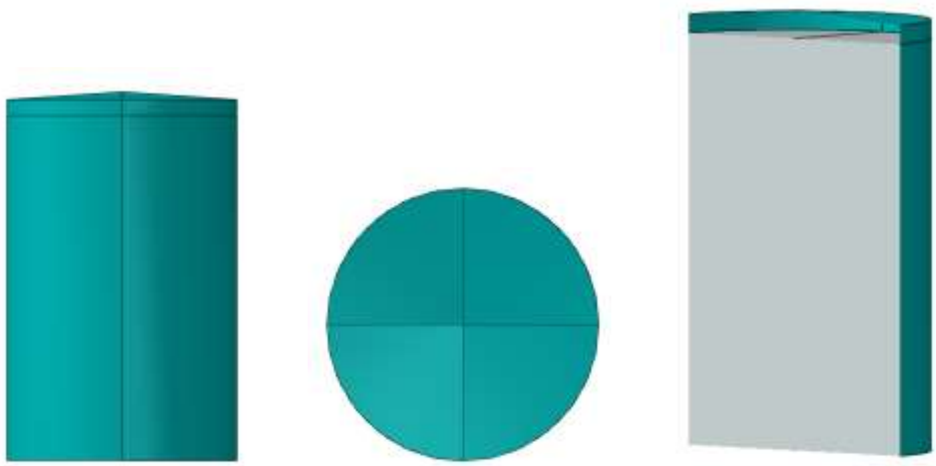


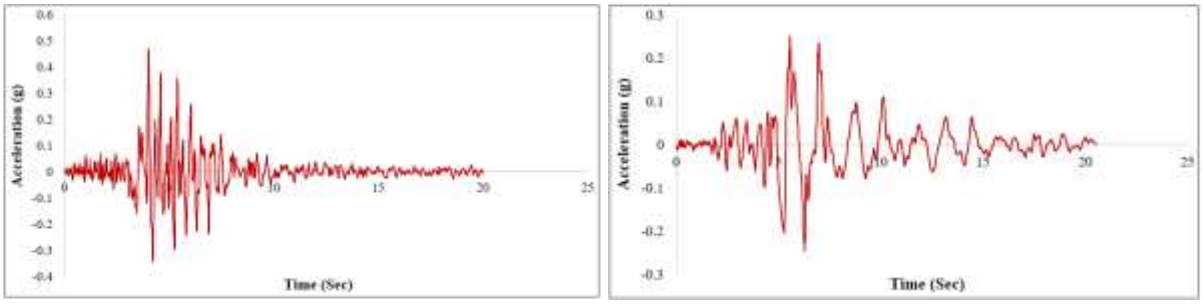
Figure 4. Bi-linear stress and strain relationship of steel


(a) (b) (c)
Figure 5 (a). Side view, (b). Top view, and (c). Tank with liquid contained

3.2 Loading, BCs, and Meshing

The analysis is conducted in three steps: step-1 comprises the geostatic step, step-2 hydrostatic Riks analysis and in the step-3 dynamic implicit analysis is carried out to capture the seismic behavior of the liquid-filled tank. Initially, the tanks behavior under static (geostatic and hydrostatic) loading for up to 2 seconds was evaluated. Following this, dynamic implicit analysis is performed using real-time history data from Friuli earthquake, Emeryville and Kobe Japan earthquake 1995 as input seismic excitations applied horizontally at the tank base. The seismic wave is applied in the boundary conditions step horizontally and the input acceleration versus time response is applied in terms of g (where g=9.81 m/s^2) in the lateral direction as shown in Figure 6 (a), (b), and Figure 7. The cylindrical steel shells are modeled using the S4R element, which is a doubly curved thin shell with reduced integration and hourglass control. This element features 4 nodes and six degrees of freedom (DoF) at each node: three translations (in the x, y, and z directions) and three rotations (about the x, y, and z axes). The liquid domain is modeled as an acoustic medium using the AC3D8R acoustic element, which has 8 nodes for 3D meshing of the liquid part. Fixed boundary conditions (zero translations and rotations) are applied for both steps, except for the free motion in the x-direction, where seismic waves are applied at the tank base.

The FE shell, 3D meshing of the liquid and soil domain is illustrated in Figure 8(a), and (b), respectively.



(a) (b)

Figure 6 Input time history (a). Friuli earthquake, and (b). Emeryville earthquake

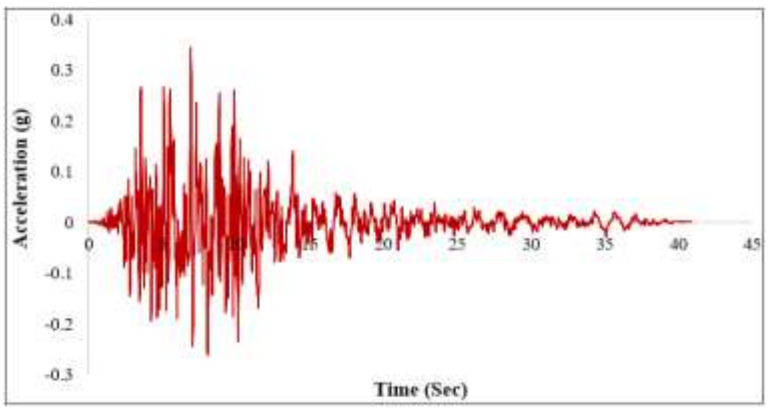
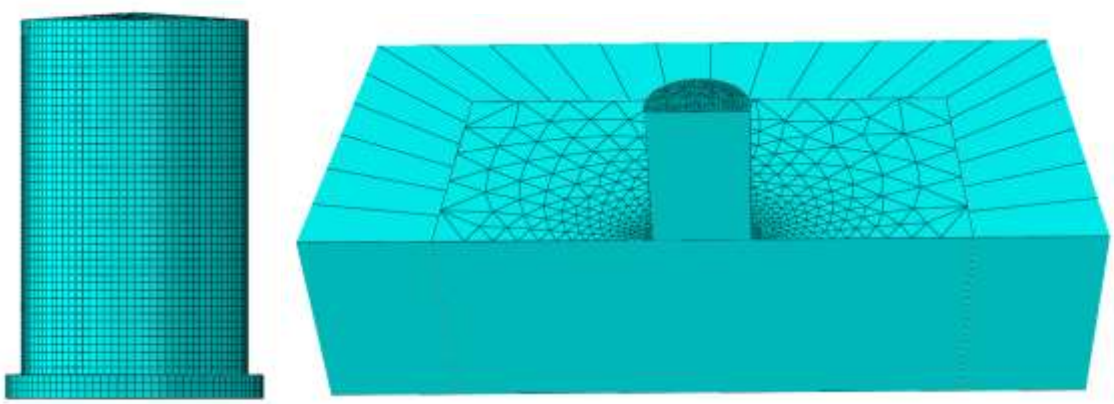


Figure 7. Input time history-Kobe earthquake.



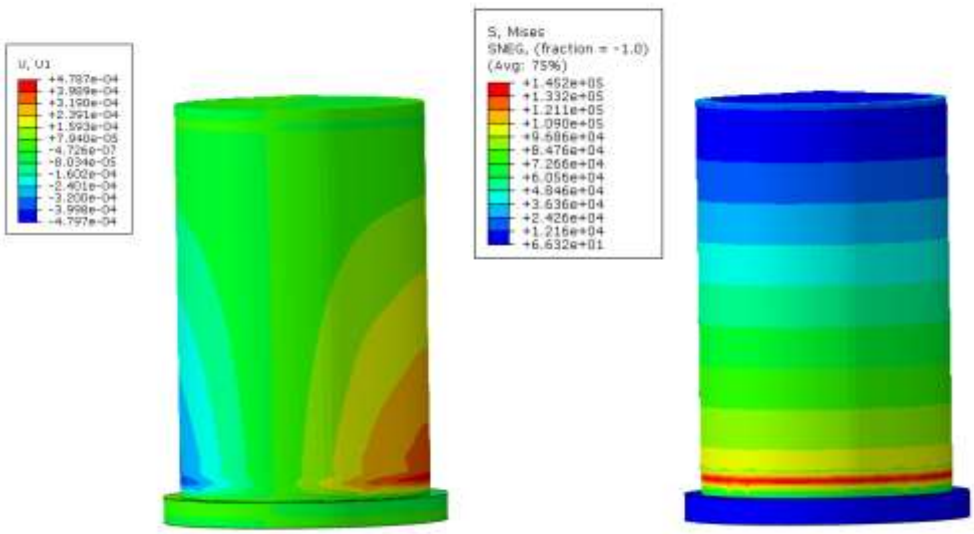
(a) (b)

Figure 8. 3D Meshing of (a). Steel Tank- S4R element, and (b). Tank with soil domain- C3D4 element and acoustic domain

4. Results and Discussion

4.1 Hydrostatic Analysis

To evaluate the behavior of a liquid-filled storage tank subjected to static loading, hydrostatic Riks analysis was performed, focusing on the deformation, stress concentration, and the distribution of circumferential stresses. The results indicate that the tank does not undergo significant deformation under static loading. Figure 9(a) illustrates the deformation of the tank under hydrostatic loading. Additionally, the maximum von-Mises stress and circumferential stress distributions were assessed. The findings reveal that the stresses are most concentrated at the tank's bottom, identifying this area as the critical region, as shown in Figure 9(b). The maximum von-Mises stress near the tank base is approximately 145.20 kPa. Similarly, the maximum circumferential stress is estimated to be around 128.10 kPa, as depicted in Figure 10.



(a) (b)

Figure 9. (a) deformation (m) response of Tank, and (b) Von-mises stresses (Pa).

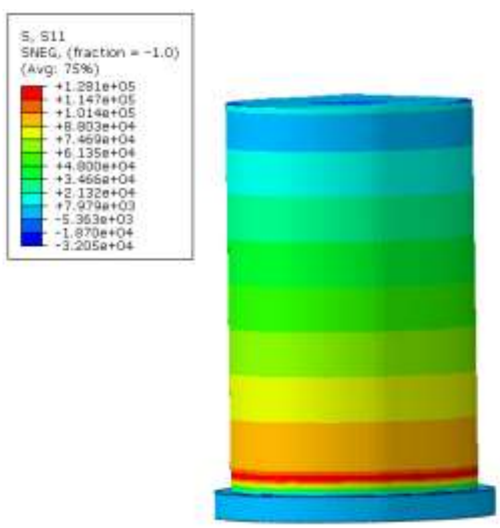


Figure 10. hoop stresses at Tank wall (Pa).

These stresses resulting from hydrostatic loading remain within the yield stress limits and do not induce plastic deformation by themselves. However, once combined with hydrodynamic stresses, the total stresses become more significant and play a critical role in the development of plastic strain, particularly near the tank bottom, where yield stresses may cause local instability. Overall, the results indicate that while the hydrostatic loading alone does not induce significant deformation or failure, it is the interaction with dynamic loading (seismic excitation) that could lead to plastic deformation and potential local instability at the bottom of the tank.

4.2 Seismic Performance Evaluation

Dynamic implicit analysis method is used for simulating the time-dependent behavior of storage tank subjected to several input seismic excitations. This method is particularly suited for problems involving large deformations, complex material behaviors, and nonlinear interactions, such as fluid-structure interaction (FSI) in liquid-filled storage tanks. In this type of analysis, both the tank structure and the liquid are modeled, with the liquid often treated as an acoustic medium that interacts with the tank wall. It provides more accurate predictions of the storage tanks involving complex FSI, which is essential for the evaluating the tank overall safety and performance under seismic events. In the current study, dynamic implicit analysis is particularly utilized to evaluate the seismic performance of a tall tank supported on rigid soil. The time history response, total hydrodynamic pressure response, stress distribution (including von-Mises and circumferential stresses), and deformation response are assessed. The results indicate that both the deformation and stress distribution are significantly altered when the tank is subjected to earthquake loading, compared to the hydrostatic loading conditions. The tank experienced a maximum deformation of 0.0249m, and the maximum stresses are about 290.01 Kpa when subjected to earthquake of peak ground acceleration 0.49g ($g = 9.81\ m/s^2$). Figure 11(a), and (b) shows the deformation response and von-Mises stress distribution of the tank. The circumferential stresses are also evaluated as illustrated in Figure 12(a). Figure 12(b) represents the maximum tensile strain at tank wall subjected to Friuli earthquake of PGA 0.49g. Similarly, when the tank is subjected to a peak ground acceleration (PGA) of 0.23g, the maximum deformation reached 0.0046m, and the corresponding von Mises stresses were 160.10 kPa. The circumferential stresses were reduced by 25% compared to stresses experienced by the tank subjected to a PGA of 0.49g. Furthermore, the results show

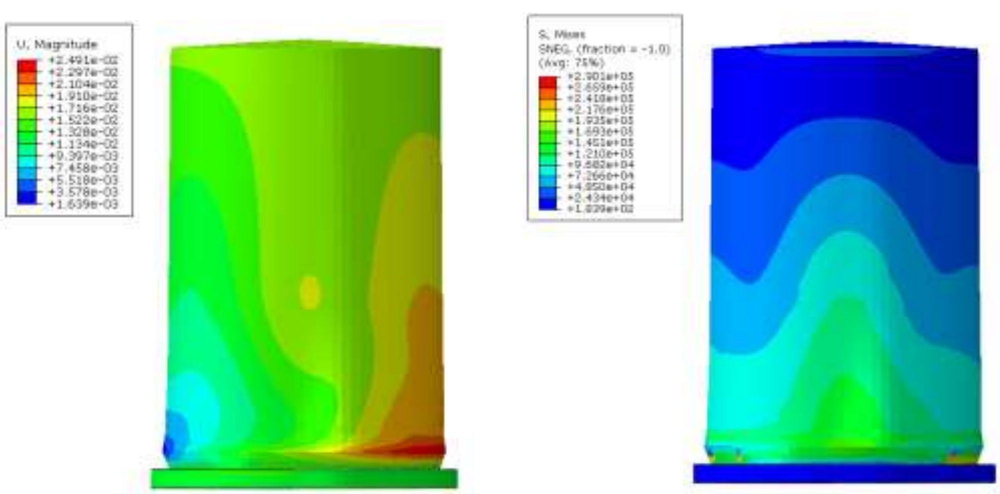
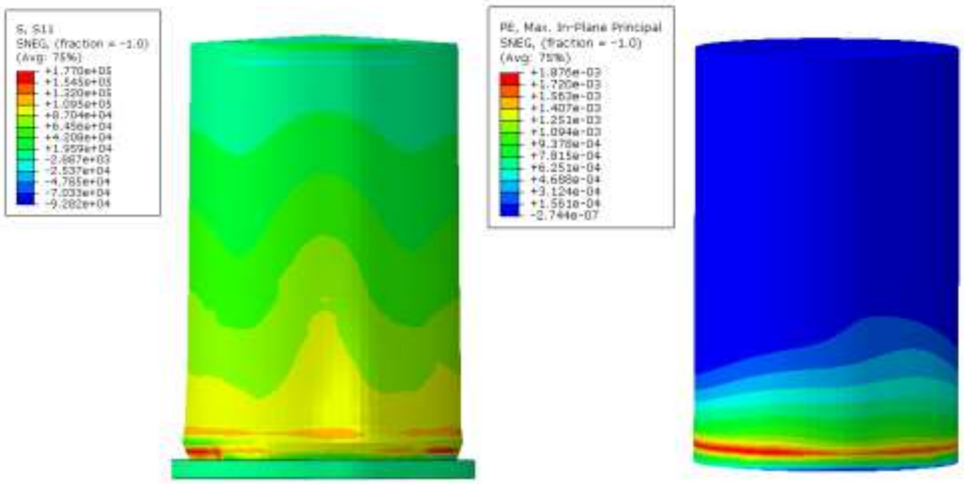


Figure 11. (a) Deformation (m), and (b) Von-mises stress distribution (Pa)

that the tank subjected to the Kobe earthquake experienced a slightly higher deformation, and the von Mises stresses reached to 140.23 KPa.



(a) (b)

Figure 12 (a). Circumferential stress (Pa), and (b). Max. tensile strain

Table 4. Results from the dynamic analysis

Input PGA ($g= 9.81\ m/s^2$)	Stresses		Peak acceleration ($g= 9.81\ m/s^2$)
	Von-Mises stresses (Kpa)	Circumferential stresses (Kpa)	
0.49	290.10	177.01	1.123
0.23	160.01	132.21	0.498
0.39	140.23	125.00	0.820

All the peak accelerations are taken at the top node of the Tank

4.2.1 Time history response

The time history response of storage tanks is a critical aspect of seismic analysis, as it provides detailed insights into the dynamic behavior of the structure under earthquake loading. By capturing variations in displacement, velocity, and acceleration over time at key locations (e.g., top, middle, and bottom nodes), this analysis helps identify peak responses that can lead to structural failure or instability. Understanding the time history response is essential for evaluating the effects of fluid-structure interaction, resonance, and energy dissipation within the tank system. It aids in the design and assessment of tanks to ensure they meet safety and performance standards under seismic conditions, ultimately preventing catastrophic failures and ensuring the safety of both the structure and its surrounding environment. Therefore, this study aims to evaluate the seismic behavior of tall tank subjected to varying input PGAs such as 0.49g, 0.23g, and 0.39g. The dynamic implicit analysis of the liquid-filled storage tank under input PGAs of 0.49g, 0.23g, and 0.39g reveals significant amplification in peak acceleration responses at the top node, highlighting the tank's

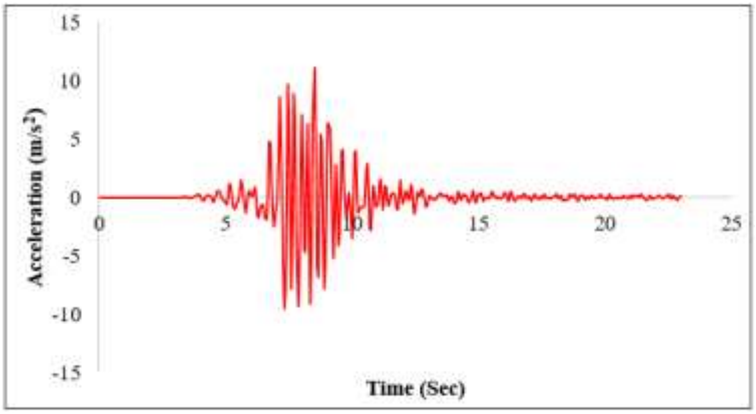


Figure 13. Time history response of Tank under Friuli earthquake

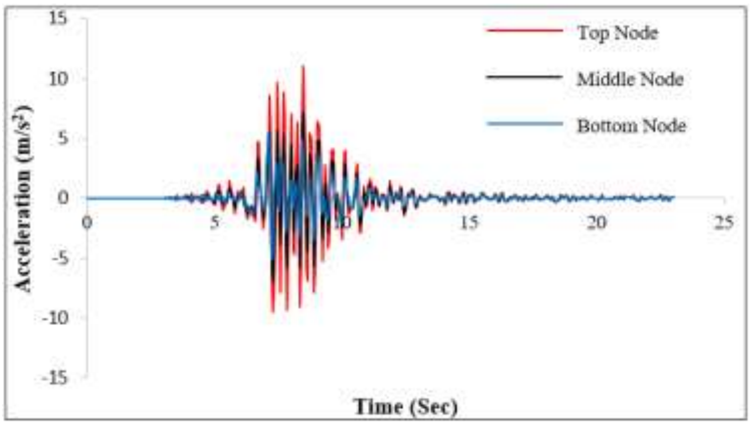


Figure 14. Time history response of Tank under Friuli earthquake

sensitivity to seismic loading. For an input PGA of 0.49g, the top node exhibits a peak acceleration of 1.123g shown in Figure 13. Figure 14 shows the comparisons of the peak acceleration at the different locations (nodes) subjected to input earthquake of PGA 0.49g. At a lower input PGA of 0.23g, the top node's peak acceleration reduces to 0.498g, reflecting a relatively diminished response under reduced seismic excitation as shown in Figure 15.

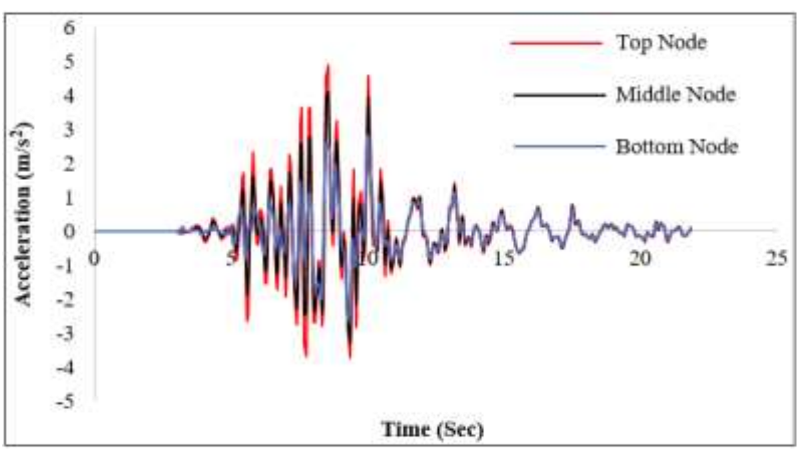


Figure 15. Time history response of Tank under Emeryville earthquake

For the intermediate input PGA of 0.39g, the corresponding peak acceleration is 0.820g, showing a dynamic response that scales with the input seismic intensity shown in Figure 16. These results emphasize the nonlinear dynamic behavior of the tank, with the top node consistently experiencing the highest acceleration, underscoring the importance of robust seismic design measures to account for such amplified responses.

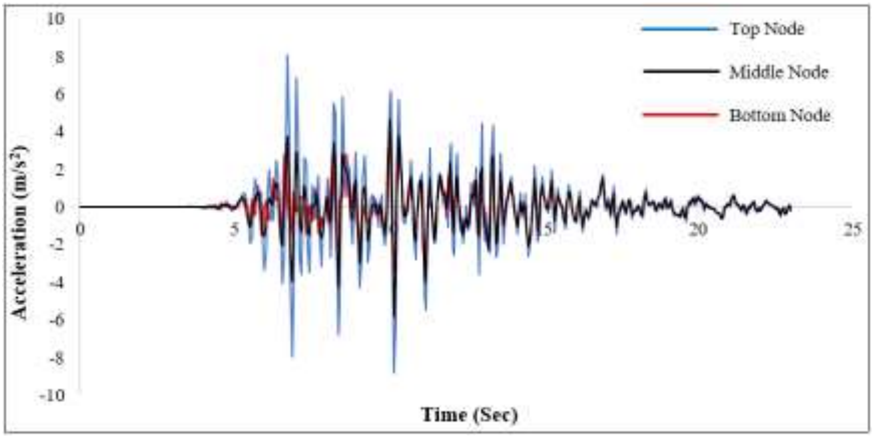


Figure 16. Time history response of Tank under Kobe Japan earthquake

Lastly, the hydrodynamic pressure response for each case is evaluated and their variations under different PGA are examined . Figure 17 shows the hydrodynamic pressure response of Tank subjected to different input PGAs. It is observed that the Tank experience maximum hydrodynamic pressure (249.90 Kpa) when subjected to earthquake of PGA 0.49g. Similarly, the hydrodynamic pressures are reduced to 48.56 Kpa, and 197.05 Kpa under lower input PGAs value of 0.23g, and 0.39g, respectively.

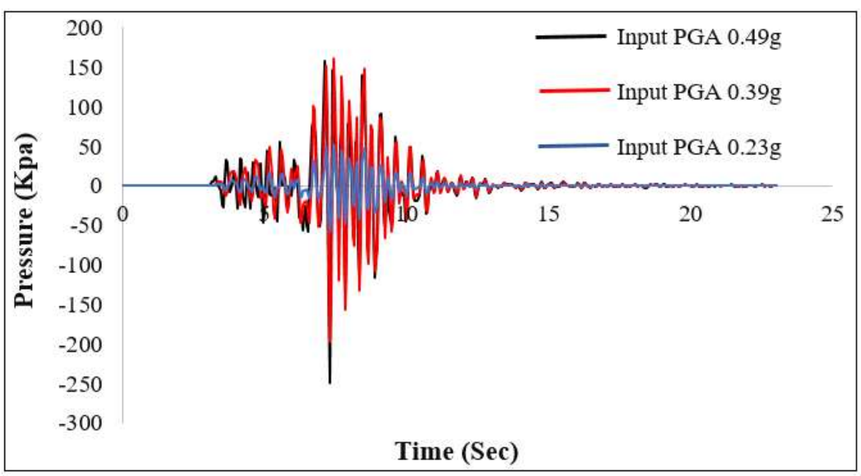


Figure 17. Comparisons of total hydrodynamic pressure (Kpa) vs time response under different input PGAs

5. Conclusions

This study has primarily investigated the dynamic behavior of a liquid-filled steel storage tank resting on rigid soil and subjected to three different real-world ground motions. The study has employed 3D finite element analysis (FEA) using ABAQUS software, with the Coupled Acoustic-

Structure (CAS) approach used to account for fluid-structure interaction (FSI). The results indicate that under static loading, both the von Mises stresses and circumferential stresses at the tank bottom remain within the yield limit, with no significant deformation observed. However, when subjected to seismic excitations, both the stresses and deformation response change significantly. Under a peak ground acceleration (PGA) of 0.49g, the tank experiences a maximum deformation of 0.0249m, with maximum von Mises stresses reaching approximately 290.02 kPa.

For a lower input PGA of 0.23g, the maximum deformation is reduced to 0.0046m, and the von Mises stresses drop to 160.10 kPa. Additionally, the circumferential stresses under this lower excitation are reduced by 25% compared to those experienced at a PGA of 0.49g. The top node of the tank exhibits a peak acceleration of 1.123g for the 0.49g PGA input. Under a reduced PGA of 0.23g, the peak acceleration at the top node is 0.498g, showing a diminished response. For the intermediate PGA value of 0.39g, the corresponding peak acceleration is 0.820g. Finally, the hydrodynamic pressure response has been evaluated for each case, with significant variations observed under different PGAs. The maximum hydrodynamic pressure of 249.90 kPa was experienced when the tank was subjected to a PGA of 0.49g. Under lower PGAs, the hydrodynamic pressures reduce to 48.56 kPa at 0.23g and 197.05 kPa at 0.39g, respectively. These results highlight the significant influence of seismic loading on the tank's structural and hydrodynamic behavior.

Future Study/Recommendations

The authors will conduct further study on incorporating nonlinear soil-structure interaction (SSI) to better understand the impact of varying soil conditions on the seismic response of liquid storage tanks. While this study focused on rigid soil, considering nonlinear soil behavior is crucial, especially for tanks supported on soft or flexible soils, which can significantly affect their performance. Additionally, sloshing effects needs to be thoroughly evaluated, which could improve predictions of tank dynamic behavior under extreme seismic conditions. This would help in refining tank designs for better resilience during seismic events. Furthermore, the research will explore specific materials such as the use of 9% Ni steel that can withstand under the cryogenic temperature -160 °C in case of storing LNG, and the incorporation of advanced seismic isolation techniques, to enhance the seismic performance of liquid storage tanks. Additionally, the integration of machine learning (ML) and deep learning (DL) techniques could help develop predictive models for seismic damage assessment, offering data-driven insights into the likelihood of structural damage during seismic events.

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