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Review

State-of-the-Art Review on the Seismic Performance Assessment of On-Ground Steel Cylindrical Tanks

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Abstract: Steel cylindrical tanks are vital structures for storing various types of liquid in industrial plants or as a component in a water distributing system. As they sometimes are used to store toxic, flammable, and explosive material, their inapt performance during an earthquake may lead to catastrophic consequences. Therefore, practicing engineers, researchers, and industry owners are concerned about their structural safety. Meanwhile, the seismic performance of liquid storage tanks is rather complex. Thus, this subject has garnered many researchers' interest in the past decades. This paper aims to briefly review the most significant studies on the seismic performance of on-ground steel cylindrical tanks. It focuses on analytical approaches and does not include experimental and on-site ones. Finally, the new horizons for the seismic performance assessment of such structures are presented herein.

Keywords: seismic performance; buckling; steel tanks; uplift; fragility

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1. Introduction

In many process industries, such as oil refineries and petrochemical plants, tanks are one of the most crucial structures. In such facilities, any interruption in the tank operation may lead to a work stoppage in the whole system. On the other hand, many storage tanks are utilized to store hazardous liquids. In such tanks, any failure that leads to a liquid spill may cause catastrophic consequences, such as explosions, significant environmental pollution, and life loss. For this reason, the appropriate performance of tanks during extreme loading conditions, such as seismic events, is a considerable concern for practicing engineers and the owners of such industries. However, the inappropriate performance of tanks during past earthquakes around the world has revealed the notable seismic vulnerability of these structures, especially pre-code ones and those designed according to the earlier editions of seismic design codes [1]. The failure of tanks during the 1983 Coalinga, the 2003 Bam, the 2006 Silakhor, and the 2012 Emilia earthquakes, in addition to several other seismic events, are examples of tank damage during earthquakes [2–7]. Among the many different stories about tank seismic failure, some are more notable and remembered because of their catastrophic consequences. For instance, the Niigata earthquake in Japan in 1964 caused a fire disaster following a tank ignition [8,9]. In addition, the destruction of three tanks caused a fire in a refinery following the 1999 Izmit earthquake in Turkey [9].

Although the static behavior of the tank is notably simple, its dynamic response is somewhat complex. When a liquid storage tank is subjected to earthquake excitation, its content begins oscillating. As a result, the pressure distribution throughout the tank shell changes from its static condition. During the dynamic response, the upper parts of the content, known as convective liquid, move in a long-period motion (so-called sloshing response). Meanwhile, the rest of the liquid (the impulsive part) moves rigidly with the tank shell. It is worth mentioning that the relative amount of the tank content behaves as an impulsive or convective fluid, depending on the ratio of the content's height to the tank diameter. The hydrodynamic pressure exerted from impulsive and convective liquid along the shell height generates an overturning moment in the tank bottom. As a result of the overturning moment, the tank tends to rock [10].

Based on their supporting condition, on-ground tanks can be categorized into two classes: unanchored and anchored. While anchored tanks are clamped to their foundation via mechanical anchors, unanchored ones are simply placed on their foundation without any restrainer. The overturning moment can cause the tank to uplift in unanchored tanks. In contrast, adequately designed anchored tanks are not expected to experience uplift. Hence, globally, researchers are interested in assessing the seismic performance of such structures.

Because of the remarkable seismic vulnerability of the liquid storage tanks, the potentially catastrophic consequences of their failure, and their complicated behavior during recent decades, numerous researchers have been attracted to study the seismic performance assessment of these structures. This paper aims to provide a platform for reviewing the significant research on the topics related to the seismic performance of liquid storage tanks. Though essential and valuable experimental studies have been conducted on this issue so far, this paper only reflects the analytical ones. To this end, it first focuses on the tank modeling techniques that are the first step for the seismic safety assessment of such structures. Then, it deals with the seismic response of tanks in Section 3. Section 4 discusses the earthquake-induced failure of tanks. It presents the most frequent failure modes of tanks. As buckling is one of the most crucial tank failure modes that attracted numerous researchers, this section mainly concentrates on this issue. Section 5 reviews the most significant research on the seismic fragility of tanks, and in Section 6 new horizons to the seismic safety assessment of tanks are presented.

2. Modeling Techniques

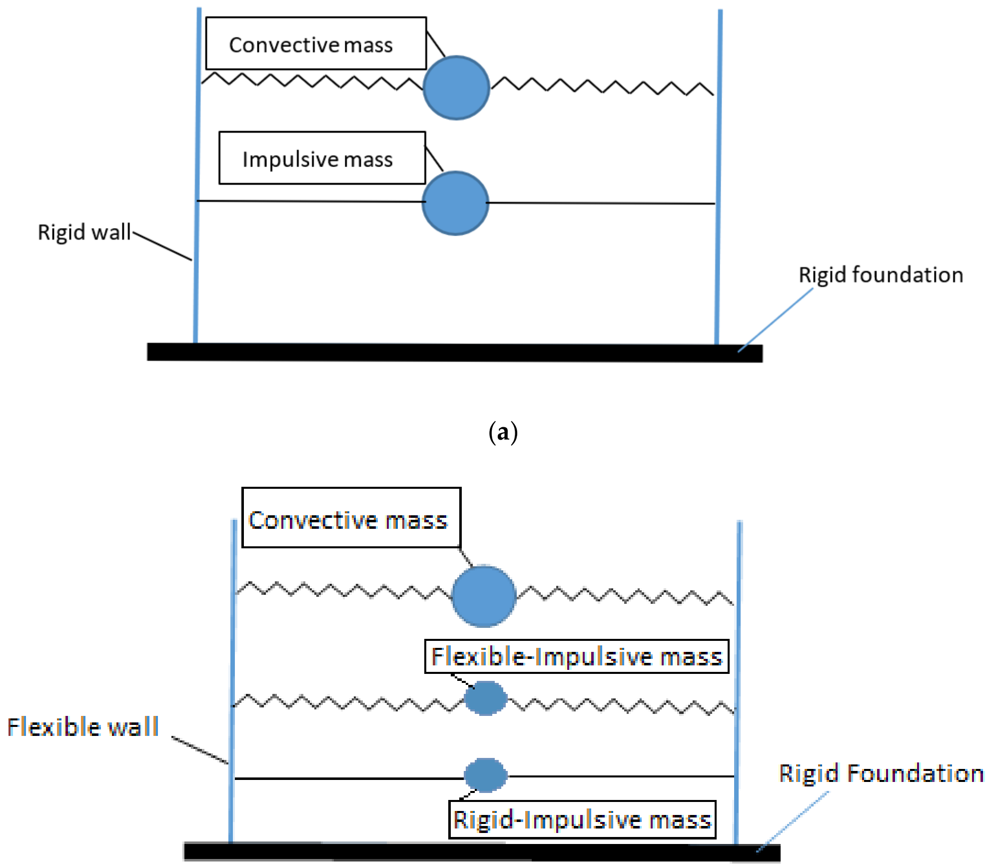
2.1. Mass-Spring Analogy

The basis of early studies on the dynamic behavior of tanks was the assumption that the tank shell and its foundation are rigid. Jacobsen [11] and Housner [12] were the first researchers who independently proposed a mechanical mass-spring analogy for such a tank. They divided the tank's content into two portions, representing impulsive and convective liquid. These portions were modeled using lumped masses interconnected to the tank's rigid wall via spring and rigid links, respectively (See Figure 1). By employing such a mechanical model, one can calculate the dynamic response of the liquid storage tanks in a linear range utilizing the generalized single degree of freedom (SDF) systems. The structural and dynamical characteristics, such as the natural period, can be calculated using the procedures presented in [13,14]. Several researchers extended this idea by reducing the simplified assumptions [14–16]. For instance, Veletsos [14] developed a simple procedure to extend Housner's model for flexible tanks. He assumed that the content is incompressible and tank and its content behave as an SDF system. On the other hand, his proposed method was an extension of that presented by Chopra [17] for simulating the dam–reservoir interaction.

Taking the effect of tank shell flexibility into account does not make a significant change to the convective hydrodynamic effects but leads to breaking the impulsive mass in the mass-spring model into two portions (See Figure 1b). One is rigid-impulsive, and the other is flexible-impulsive mass. Therefore, considering the shell deformability might change the impulsive pressure distribution along the tank height compared to rigid tanks. However, such differences are insignificant where the content's height-to-diameter ratio is less than 1 [10,16]. In other words, shell flexibility effects are negligible in comparatively broad tanks, especially thicker ones, but they are significant in notably slender ones [10,18].

Wozniak and Mitchell [19] employed the mass-spring analogy to provide the seismic design criteria for welded steel liquid storage tanks. They utilized Housner's model to calculate the hydrodynamic loads applied to tanks during an earthquake. Later, API

650 [20] adopted their proposed seismic design procedure for welded steel tanks. Since then, various seismic design codes and design guidelines included the mass-spring mechanical models. It is still the basis of the latest editions of seismic design codes and guidelines, such as API 650 [21], Eurocode 8 [22], NZSEE [23], and the Iranian seismic design code for oil industries (so-called code 038) [24].



(**b**)

Figure 1. Mass-spring analogy for (**a**) rigid tanks, (**b**) flexible tanks.

2.2. Numerical Modeling

In the late 1970s and early 1980s, researchers started to study the linear dynamic behavior of liquid storage tanks using finite element (FE) techniques. Perhaps, Haroun [25] was the first scholar who implemented the FE to solve the vibration problem of the cylindrical liquid-filled tank. He discretized the tank wall through linear shell elements and considered the effect of content using boundary solution techniques. Since then, numerical simulation approaches were rapidly employed by researchers to investigate the hydrodynamics of tank-liquid systems [26–31]. So far, a notable number of numerical techniques have been presented for estimating the seismic behavior of tanks. Among them, FE, boundary element (BE), and the coupled FE-BE approaches are the most frequently used methods.

2.2.1. FE Techniques

In many of the available numerical studies, the FE method was employed for investigating the dynamic response of cylindrical liquid storage tanks [32–36]. Despite the fact that the seismic performance of steel cylindrical tanks during large earthquakes can be significantly nonlinear, early FE-based simulations of cylindrical tanks under the seismic actions were based on the assumption of linear behavior of the tank. It is evident that the main reason for such simplifications was the limitation of computer hardware and software at that time. Gradually, by increasing the capability of computer systems, nonlinear FE procedures were significantly developed. Such progresses empowered the researchers to consider different sources of material and geometric nonlinearities in the FE modeling of tank-fluid systems under earthquakes. The advancement of nonlinear FE techniques has brought the ability to simulate the actual performance of liquid storage tanks during natural earthquakes [37,38]. In recent years, several researchers focused on modeling the seismic behavior and performance of steel liquid storage tanks [39–44]. Although the tank's structural modeling is somewhat the same in available articles, diverse techniques are utilized for modeling the content.

Despite the variety of techniques in fluid modeling in tank FE modeling, one can categorize them into two main classes: using specific fluid elements and employing the added-mass method. It is worth mentioning that utilizing fluid finite elements covers a variety of FE-based procedures. Eulerian and Lagrangian approaches are two classical descriptions of motion in fluid–structure interaction problems, such as tank hydrodynamics [45]. The crucial drawback of Lagrangian FE procedures is that they are inappropriate for large deformations [46], whilst Eulerian methods are not sensitive to large movements. Therefore, for the fluid–structure interaction problem of a tank subjected to seismic actions, one can also deploy the Eulerian–Lagrangian approach that utilizes an Eulerian mesh for fluid and Lagrangian one for the tank structure [47]. Utilizing the specific FE mesh for the tank's content, one can precisely simulate the tank and its content's seismic behavior (See Figure 2). Therefore, numerous researchers have employed this procedure to assess the seismic performance of tanks [48–50]. However, its most significant shortcoming is that it is time-consuming and requires considerable memory space. On the other hand, it may encounter convergence problems. Further, depending on the selected FE procedure, some may not be appropriate for solving problems in which the large deformation is significant. Hence, some scholars and practicing engineers prefer to utilize the added-mass procedure. The idea of effective mass applies to silos and liquid containers [51]. Westergaard [52] was the first researcher that proposed the added-mass approximation to consider the dam–reservoir interaction. In this method, the effective liquid mass is added to the tank wall to account for the inertia of the liquid during the tank vibration. Barton and Parker [27] implemented added mass approximation in cylindrical tanks. They considered the effective mass of liquid utilizing two different approaches. In the first approach (so-called enhanced density model), they artificially increased the density of the tank shell material up to the level of the liquid surface to consider the mass of the tank's content. The crucial drawback of this assumption is that it is attributed to every degree of freedom at the shell nodes, and not only in the radial direction. This attribution is not consistent with the actual behavior of the tank-content system [53]. In the second approach, they utilized SDF mass elements and added them to every node on the tank shell under the fluid surface. They uniformly distributed 72% of the fluid's mass to the tank shell. This assumption is also inconsistent with the actual behavior of the content during the dynamic tank–fluid interaction, which deals with the non-uniform distribution of the hydrodynamic impulsive pressure. In recent years, many researchers have utilized mass elements for modeling the content [54–58]. They connect the nodal masses to the shell nodes using massless rigid links and restrain all degrees of freedom of the mass element except in the radial direction (see Figure 3). Through this technique, they are able to attribute the added mass only to the radial direction. In addition, they derived the value of nodal mass from the impulsive hydrodynamic pressure. This assumption is significantly more convenient with cylindrical tank hydrodynamics compared to uniform mass distribution. The impulsive pressure at a particular node of the tank shell (P_i) is a function of its distance from the tank base (z) and the angle between that node and the direction of strong ground motion (θ). It can be formulized as follows:

$$P_i(\eta,\theta,t) = C_i(\eta).\rho.\ddot{x}_g(t).cos\theta \quad (1)$$

where, $\ddot{x}_g(t)$ is the time-dependent acceleration of the excitation, $\eta = z/H_L$, $C_i(\eta)$ represents the impulsive pressure distribution along the tank's height, and H_L is the height of liquid. One can use C_i can be calculated in terms of the convective pressure distribution $C_{cn}(\eta)$ as follows:

$$C_i(\eta) = 1 - \sum_{n=1}^{\infty} C_{cn}(\eta) \tag{2}$$

The function $C_{cn}(\eta)$ can be calculated as follows:

$$C_{cn}(\eta) = \frac{2}{\lambda_n - 1} \frac{\cos h[\lambda_n (H_L/R)\eta]}{\cos h[\lambda_n (H_L/R)]} \tag{3}$$

where, λ_n is the nth root of the Bessel function and R is the radius of the cylindrical tank. Several researchers demonstrated that, using the first three roots of the Bessel function (λ_1 = 1.841, λ_2 = 5.311, and λ_3 = 8.536) is sufficient to comparatively obtain accurate values for C_{cn} [47,52].

The nodal lumped masses corresponding to the tank's base and the surface of content ($m_{i'}$) can then be calculated using Equation (4). Also, for interior shell nodes, the corresponding lumped mass can be determined using Equation (5).

$$m_{i'} = \frac{P_{i'}}{2} \frac{\Delta h}{\ddot{x}_g(t).cos\theta} \tag{4}$$

$$m_i = P_i \frac{\Delta h}{\ddot{x}_g(t).cos\theta} \tag{5}$$

Δh is the distance between the adjacent nodes in vertical direction.

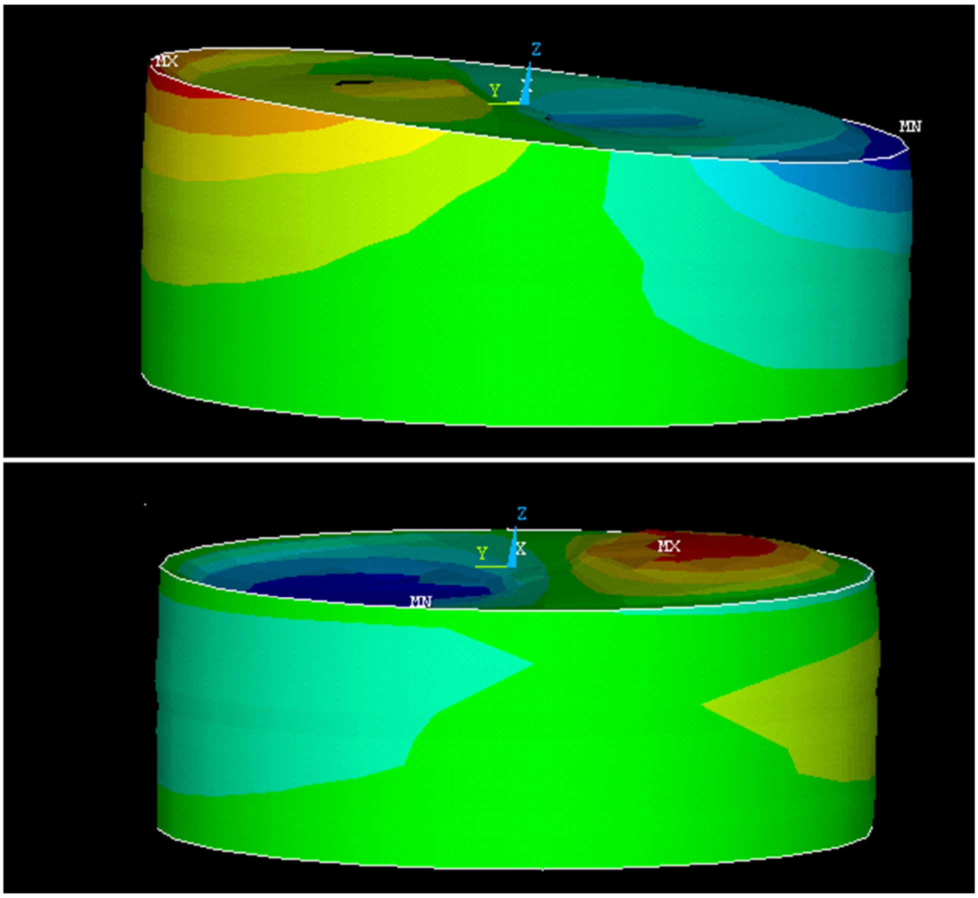


Figure 2. Seismic response of a fluid in two stages of a response–history FE analysis.

The advantage of the added-mass approximation is that it is faster than specific fluid elements and requires less memory space. In addition, added-mass-based models often have a more acceptable convergence rate than those modeled with fluid elements. On the other hand, they are consistent with large displacement finite elements. This benefit would be the reason for the spread implementation of the added-mass procedure for the buckling assessment of tanks. However, the most vital shortcoming of the added-mass method is that it neglects the effect of convective liquid and is not applicable to simulate the sloshing behavior of the content.

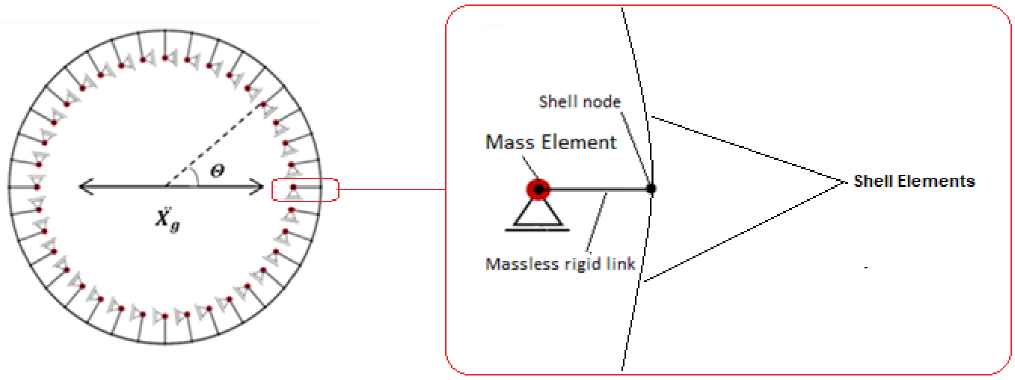


Figure 3. A schematic of added-mass model.

2.2.2. BE and Coupled FE-BE Techniques

The boundary element (BE) method is an appropriate alternative to simulate the tank content numerically. The advantage of this technique is that in BE modeling, one can discretize the boundaries instead of the whole solution domain and this consequently reduces the calculation time and the required memory [59]. Despite the magnificent benefits of BE simulation for the liquid, it is less attractive compared to FE procedures for modeling the shell structures, especially in the nonlinear range of behavior. Therefore, some researchers proposed the application of BE and FE in a coupled system. In such a system, one can model a tank and its content using the FE meshing and BE methods, respectively [60–62].

2.2.3. Other Approaches

In addition to the abovementioned techniques, several other approaches are available that take the effect of fluid dynamic-response in liquid storage tanks into account. Computational fluid dynamic (CFD) methods are a suite of numerical techniques for solving the fluid flow problem. In general, the basis of most CFD techniques are Navier–Stokes equations. Researchers have employed CFD techniques to solve several tank-fluid problems, such as wind and wave effects on tanks that deals with external fluid effects on cylindrical tanks [63–65]. CFD methods have also been employed to investigate the hydrodynamic effects of the tank content due to earthquakes [66–68].

3. Seismic Response

On-ground tanks are classified into two categories concerning their supporting systems: un-anchored and mechanically anchored. While the mechanically anchored tanks are clamped to their foundation utilizing mechanical connections known as anchors, unanchored tanks are simply placed on the foundation without any restrainer. As a result of the combined action of the hydrodynamic pressure and the inertia of the tank structure, liquid storage tanks tend to exhibit a rocking motion during an earthquake. Therefore, unanchored tanks may experience partial base uplifting. Even mechanically anchored tanks may experience uplift because of anchor failure or inappropriate performance of their foundations. The tank uplift is not a failure mode for an unanchored tank, but it would be a reason for several failure modes in liquid storage tanks [10]. When a tank experiences base uplifting, its contact between the shell and foundation reduces. As a result, the shell's axial compression in non-uplifted portions increases. In addition, the uplifting seismic response generates significant stresses on the tank bottom plate in uplifted areas. The uplifting behavior of the tank is a complicated dynamic response. It is geometrically nonlinear and may be associated with material nonlinearity. Therefore, reliable uplift modeling is a complex procedure. Researchers started to assess the seismic behavior of uplifting tanks in the 1970s. All the early models of uplifted tanks were based on the mechanical mass-spring analogy [69–71]. Some researchers have focused on the behavior of the baseplate and tried to provide an analytical model to estimate the potential tank uplift in unanchored tanks. Table 1 presents some significant analytical models for calculating the potential tank uplift.

Table 1. Summary of the significant models for tank uplift.

Provider	Description	Simplifications and Drawbacks	Reference
Wozniak and Mitchell	An analytical model based on the uplift of a strip baseplate. The model was adopted by some early editions of API 650.	Neglecting the effect of membrane action.	[19]
Cambra	An empirical–analytical model. The modified version of the model was adopted by NZSEE.	Simplifications in the magnitude of the axial and shearing force.	[72]
Malhotra and Veletsos	An analytical model based on the uplift of a beam model	Considering the baseplate as a semi-infinite beam of constant width resting on a rigid foundation.	[73]
Malhotra and Veletsos	An analytical model based on the uplift of a beam model	Considering the baseplate as a semi-infinite beam of constant width resting on a flexible foundation.	[74]
Malhotra and Veletsos	An analytical model based on the uplift of a beam model. Considering the large deformation effects. A solution was made based on the Ritz energy method.	Considering the baseplate as a semi-infinite beam of constant width resting on a flexible foundation.	[75]
Ahari et al.	An analytical model based on the uplift of tapered beam.	Considering the baseplate as an ensemble of tapered beams. Their solution technique may encounters lead to chaotic response around the exact solution for the small uplift lengths.	[76]

As previously mentioned, the uplift modeling is inherently complicated because of the significant material and geometric nonlinearity. Therefore, although all the above models provide remarkable advancement in estimating the tank uplift, they are associated with various levels of simplifications. However, the progress in numerical analysis approaches, parallel to the recent technological developments in computer hardware, made a notable mutation in this issue. Several FE-based numerical studies have been conducted to evaluate the tank uplift during earthquakes. As depicted in Figure 4, employing FE simulations, one can appropriately monitor the uplifting history of critical nodes. Vathi and Karamanos employed nonlinear static analysis to study the base uplifting mechanism of two cylindrical liquid storage tanks [77]. They have also focused on the low-cycle fatigue induced by a repetitive tank uplift in another project [78]. Bakalis and Karamanos [79] performed detailed investigations on the mechanism of the tank uplift based on the nonlinear static analysis. Miladi et al. [55] conducted substantial incremental dynamic analyses on unanchored tanks and evaluated the effect of random geometric imperfections of tank shells on tank uplift and showed that tank imperfection do not play a significant role in tank uplift (See Figure 5). Spritzer and Guzey [80] employed nonlinear FE analysis to estimate the uplift of cylindrical roofless tanks on flexible foundations. Razzaghi and Eshghi [81,82] classified unanchored tanks based on their uplift behavior and demonstrated that the uplifting response of tanks with H/D < 0.5 notably differs from the others. They categorized such tanks into broad tank classes and showed that despite slender tanks, their uplift potential remarkably decreases when the relative amount of content reduces. Some other researchers provide FE-based simplified methodologies to study the tank uplift [83,84]. In addition to the above studies, many other articles have provided valuable insight on this subject [85–90].

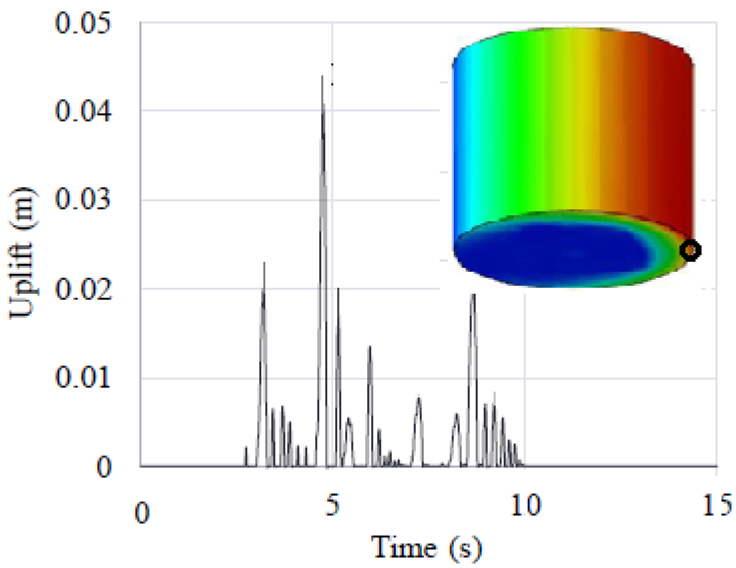


Figure 4. A displacement contour of an uplifted tank and the uplifting response history of its critical node, obtained from a FE simulation.

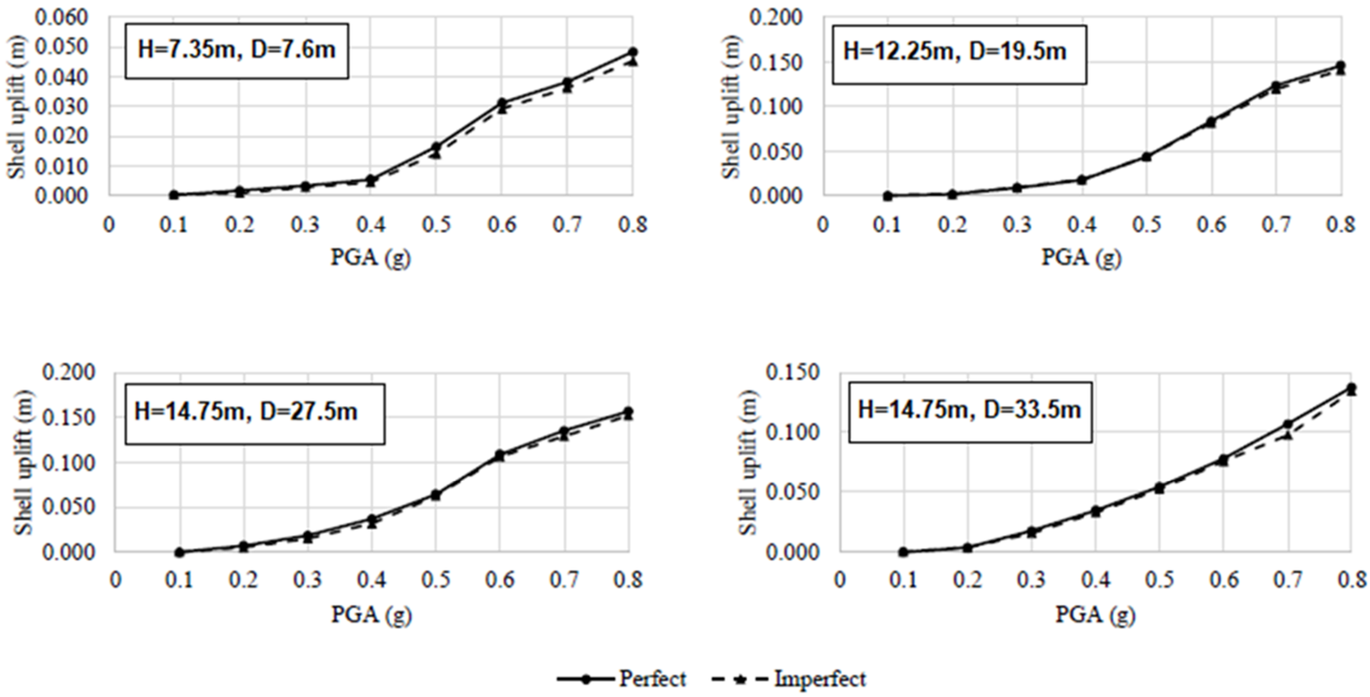


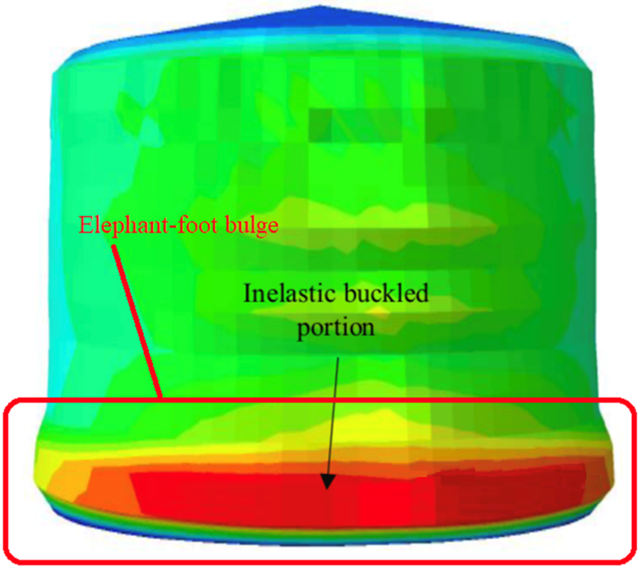
Figure 5. Comparison of the average tank uplift of perfect and imperfect tanks obtained from ten sets of incremental dynamic analyses (regenerated from [53]).

4. Earthquake-Induced Failure Analysis

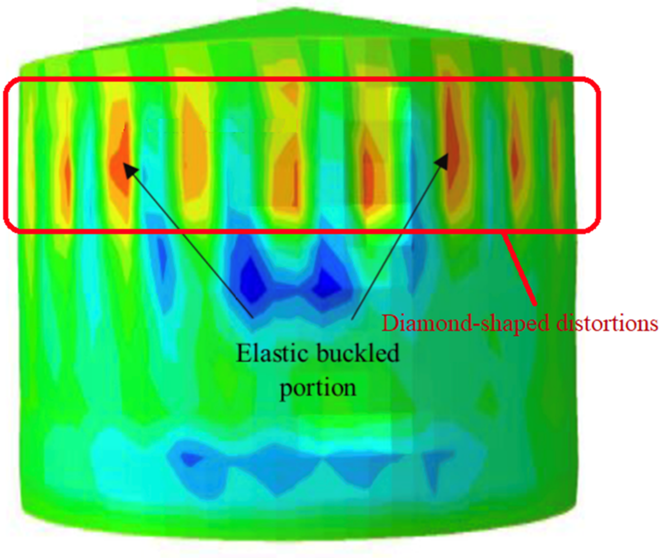
Tank failure can occur in several forms, such as shell buckling (including elastic and inelastic buckling), local shell wrinkling, bottom-plate rupture, and damage to appurtenances. Razzaghi [10] listed the tank's most frequent failure modes, their reasons, and potential aftermaths. Since shell buckling is the most frequent failure mode that may lead to catastrophic consequences, it has been the subject of numerous research projects in recent decades.

4.1. Buckling Analysis

Since steel cylindrical tanks are generally thin-walled structures, shell buckling is one of their most frequent failure modes. Therefore, several researchers have focused on the buckling assessment of steel cylindrical tanks because of earthquakes. As indicated in Figure 6, depending on the relative thickness of the tank's shell, they may buckle in any of two forms: inelastic (elephant's-foot buckling) and elastic (diamond-shaped buckling). While inelastic buckling that usually takes place in relatively thicker shells, elastic buckling often occurs in comparatively thinner ones [10,55]. It is worth noting that the main difference between the elastic and inelastic forms of buckling is that before the elastic buckling, no plastic strain is generated in the buckled areas of the shell [10].



(**a**)



(**b**)

Figure 6. Different types of tank shell buckling (**a**) inelastic (**b**) elastic resulted from a FE dynamic analysis.

4.1.1. Analytical Relations

In the early years of the 20th century, Lorenz, Timoshenko, and Southwell independently studied the buckling of cylindrical shells under purely axial loads [91–93]. Their attempts led to the derivation of a formula to estimate the buckling stress of a perfect elastic steel cylindrical shell (so-called classical buckling stress) as follows:

$$\sigma_{cl} = 0.605E\frac{t}{R} \tag{6}$$

where, t is the shell thickness, E is the Young's modulus, and R is the shell's radius. However, subsequent studies showed that for several reasons, in practice, the buckling strength is less than the classical stress [94]. Further studies revealed that shell imperfections were the most significant factor that made the difference in the buckling strength in the classical buckling stress [95–97]. The modified form of Equation (6) is the basis of practical relations for the elastic buckling of cylindrical shells in some seismic design codes [98].

Elephant's-foot buckling usually occurs because of the combined axial stress and local bending. For this reason, it usually takes place in the lower parts of the liquid storage tanks near the baseplate. The bending moment generates in lower parts, and appears because of the cantilever behavior of the tank in a vertical direction. Some forms of inelastic buckling (so-called elephant's-knee buckling) may appear in the thickness-changing locations, where the local bending moment is generated because of the possible eccentricity of the thrust line in thickness-changing portion.

In the 1980s, Rotter [99] presented a relation for the inelastic buckling stress in steel cylindrical tanks that has been one of the most essential formulas for evaluating the inelastic buckling of such tanks. NZSEE and Eurocode8 are two of the seismic design codes that adopted Rotter's formula for estimating the inelastic-buckling capacity of a steel cylindrical tank as follows:

$$\sigma = \sigma_{cl}\left(1 - \left(\frac{P\,R}{f_y\,t}\right)^2\right)\left(1 - \frac{1}{1.12 + r^{1.5}}\right)\left(\frac{r + \frac{f_y}{250}}{r + 1}\right) \tag{7}$$

where, $r = R/(400t)$, P is the total internal pressure and f_y is the yielding stress of steel.

4.1.2. Numerical Studies

Following the progress in computer hardware and numerical solving techniques, significant numerical studies were performed to investigate the buckling of cylindrical tanks. The basis of some of them were static approaches, and others were based on a dynamic standpoint.

Static Buckling Assessment

Several numerical studies are available on the static buckling of steel tanks. Virella et al. [100] proposed a static nonlinear procedure for buckling assessment in cylindrical tanks. They considered geometric and material nonlinearity in their study. Sobhan et al. [101] employed the pushover analysis to investigate buckling in anchored tanks. Miladi and Razzaghi [102] performed substantial analyses to evaluate the buckling of steel cylindrical shells with circular cutouts. They utilized the nonlinear incremental static procedure considering large-deformation effects. They studied the influence of various arrangements of circular cutouts on the buckling and post-buckling behavior of cylindrical shells. In addition to the above studies, several others provide significant insight into the buckling of tanks via the static numerical procedures [103–105].

Dynamic Buckling Assessment

The tank's shell buckling during a seismic event is a dynamic phenomenon highly dependent on the dynamic properties of the tank alongside the earthquake characteristics. Although the abovementioned studies were comprehensible and easy to employ, they ignore the dynamic nature of buckling during an earthquake. Budiansky and Roth proposed a methodology to investigate the dynamic buckling of spherical shells [106]. Later, their procedure was adopted for dynamic buckling assessment of various types of thin-walled structures, such as cylindrical tanks. The basis of this approach is incremental dynamic analysis (IDA) and successive measurement of the radial deformation of the tank shell in control nodes for every stage of IDA. The purpose of this procedure is to monitor the shell nodes for a sudden jump in one of the IDA steps. The smallest peak ground acceleration (PGA) that creates such a jump is a critical PGA. In recent years, the Budiansky–Roth procedure has been implemented in many studies to evaluate the dynamic buckling of liquid storage tanks [107–110]. For instance, Miladi and Razzaghi employed it to assess a buckling in an existing tank damaged during a natural earthquake [38]. They adopted the same procedure to investigate the effect of random imperfection on the dynamic buckling of cylindrical tanks in another study [55]. Buratti and Tavano [56] utilized the Budiansky–Roth method to develop buckling fragility curves for liquid storage tanks.

4.2. Other Failure Modes

Comparatively, a few articles are available on the earthquake-induced failure modes other than buckling. Vathi et al. [111] presented a performance criteria for various types of local failure modes, such as damage to the attached pipe and failure of the shell-to-pipe connection. Cubrinovski et al. [112] investigated the seismic response of pile-supported tanks subjected to liquefaction. Prinz and Nussbaumer studied the capacity of radial baseplate welds [113]. In addition, some researchers focus on the low-cycle fatigue of the shell-to-baseplate connection of the unanchored tanks [114–116].

5. Fragility Analysis

In the late 20th century, the idea of evaluating the seismic performance of structures through a probabilistic approach was gradually expanded. Soon, fragility curves were developed for diverse structural systems, such as tanks. Fragility curves are statistical functions that could estimate the probability of reaching a certain level of damage state or higher versus an intensity measure (IM). Hence, derivation of them requires a dataset of the seismic performance of that structure. One can assemble such a dataset through at least four methods: utilizing expert judgment, employing empirical data, using numerical analysis, and the hybrid technique. The problem that existed at that time as a limitation for the derivation of these functions for tanks was the lack of sufficient data on their seismic performance. On one hand, there was not a reliable database with adequate data on tank performance during natural earthquakes, and on the other hand, using numerical techniques required substantial analyses for a significantly nonlinear system. Therefore, early seismic fragility curves for liquid storage tanks were developed by HAZUS based on expert opinions [117]. Soon, O'Rourke and So [118] prepared a valuable dataset of the seismic performance of the liquid storage tanks during the pre-1995 earthquakes to develop the first empirical fragility curves for steel cylindrical tanks. Although their database includes many uncertain data, they provided fragility functions reasonable for engineering purposes. In addition, they brought valuable insights into two crucial sources of uncertainty in the seismic fragility assessment of tanks: the relative amounts of content and the height-to-diameter ratio of tanks. Razzaghi was the first researcher who presented analytical fragility curves for steel cylindrical tanks [10,81,82]. He developed IDA-based fragility curves for unanchored liquid storage tanks. Since then, several seismic fragility curves have been developed for liquid storage tanks [119–126]. Table 2 presents some of the most significant curves.

Table 2. A summary of the significant fragility curves for steel tanks.

Provider/Reference	Category	Description	IM
NIBS (1999) [117]	Judgmental	Separate expert opinion-based fragility curves for anchored and un-anchored tanks.	PGA
O' Rourke andand So (2000) [118]	Empirical	Empirical fragility curves for unanchored and anchored tanks pre-1995 US seismic events.	PGA
Razzaghi (2007) [81,82]	Judgmental–Empirical–Analytical	Separate judgmental, empirical and analytical fragility curves for unanchored tanks in terms of H/D and %Full.	PGA
Berahman and Behnamfar (2007) [119]	Hybrid	Bayesian-based fragility curves for unanchored tanks using historical data and ALA database.	PGA
Berahman andBehnamfar (2009) [120]	Hybrid	Fragility curves for elephant's foot buckling and welding failure of shell-to-bottom plate junction using numerical analysis and Bayesian updating technique.	$Sa(T_i)$
Buratti and Tavano (2014) [56]	Analytical	Analytical fragility curves for shell buckling using incremental dynamic analysis.	PGA, PGV, PGD, PSA
Razzaghi and Eshghi (2015) [1]	Analytical–Empirical	Analytical fragility curves for pre-code unanchored tanks in terms of H/D and %full as well as an empirical fragility curve using data collected following three major earthquakes in Iran.	PGA
Cortez and Prinz (2017) [121]	Analytical	Seismic fragility curves for unanchored tanks considering fatigue and local instability	PGA
D'Amico and Buratti (2019) [122]	Empirical	Empirical fragility curves based on observed seismic performance of tanks and Bayesian approach.	PGA
Phan et al. (2019) [123]	Analytical	Analytical fragility curves for shell buckling and shell-to-bottom plate rotation using pushover analysis of simplified models.	$Sa(T_i)$
Mayorga et al. (2019) [124]	Analytical	Natech-based parametric fragility curves	PGA
Yazdanian et al. (2021) [125]	Empirical	Empirical fragility curves for stainless steel wine tanks based on the dataset of the seismic performance of approximately 3400 wine tanks in New Zealand.	PGA

ALA = American lifeline alliance, PGV = Peak ground velocity, PGD = Peak ground displacement, PSA = Pseudo spectral acceleration, Sa(Ti) = Spectral acceleration corresponding to the period of impulsive mass.

6. New Horizons

All of the above studies have played a vital role in generating approaches to understand the seismic behavior and performance of a structure as complex as liquid storage tanks. But, several unclear aspects of this issue still exist.

6.1. Modeling the Random Defects and Imperfections

Steel cylindrical tanks may suffer from defects, such as corrosion. As defects can change the tank's dynamic properties and the strength of its structural components, it is crucial to consider their effects on the seismic performance of tanks. Several researchers took the effects of corrosion on the seismic performance of tanks into account [127–129].

However, the corrosion pattern of tanks is random, and in the above studies, deterministic patterns of corrosion are considered. Such simplifications usually lead to conservative results. Therefore, to obtain more reliable estimations about the tank's seismic performance, one shall focus on the random characteristics of corrosion. Based on the author's literature survey, random simulation of the corrosion in tanks does not investigate in the articles related to the seismic performance of tanks.

On the other hand, tanks include different types of imperfections. Some inherently exist in curved shell elements of the tanks, and others are created at the junction of those elements during the welding procedure. In recent years, Miladi and Razzaghi have performed comprehensive research on the effect of different imperfections on the seismic performance of unanchored tanks [38,55]. However, further substantial research is required to achieve a comprehensive conclusion about the imperfection effects on the seismic performance of tanks.

6.2. Employing Artificial Intelligence

Nonlinear response history analyses are widely used to estimate the seismic performance of tanks, and they often require notable analysis time and a considerable amount of computer memory. Also, during nonlinear analyses, one may encounter unwanted situations, such as convergence difficulties. Hence, nonlinear response history analyses are costly and time-consuming. On the other hand, the empirical data from the performance of the tanks during an earthquake are not enough to obtain comprehensive information about the seismic performance of tanks. In this situation, one can employ artificial intelligence-based approaches to improve the abovementioned problems. However, only a few studies are available on this issue [130].

6.3. Novel Techniques to Improve Tank Seismic Performance

Recently, several researchers have focused on novel techniques to improve the seismic performance and behavior of tanks. Najmabad et al. [131] proposed the application of shape memory alloys (SMA) as mechanical anchors. They compared their effects on the shell buckling with those of regular anchor bolts and showed that SMA anchors could improve the buckling performance of unanchored tanks. Several other researchers have focused on the active and passive control of storage tanks. Providing seismic based-isolation systems has garnered the attention of many researchers till now [132–135]. However, in recent years a new generation of seismic isolating systems has been proposed. For instance, Rawat and Mastagar investigated the application of oblate spheroid base isolators on the seismic response of tanks [136,137]. Some other researchers studied the application of different arrangements of inerter base isolators to control the seismic response of liquid storage tanks [138–141]. In addition, several other researchers have focused on utilizing various types of dampers on base-isolated liquid storage tanks [142–145].

7. Conclusions

This paper has outlined an overview of the seismic performance assessment of liquid storage tanks by presenting a review of current knowledge on different aspects of the analytical and numerical approaches. The seismic performance assessment of tanks is associated with considerable complexities. The seismic performance of tanks during devastating earthquakes includes geometric and material nonlinearity. In addition, the tank's seismic performance is dependent on diverse parameters, such as random imperfections. Although the basis of early studies was restricting simplifications, the recent advancement in numerical analysis techniques and computer technology developments have indicated new horizons to evaluate the seismic safety of tanks. In other words, as different aspects of the seismic performance of tanks still require development, this field of study is strongly active.

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