POLITECNICO DI TORINO

Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture

Corso di Laurea Magistrale in Ingegneria Del Petrolio

Sessione di Laurea novembre 2024

Tesi di Laurea Magistrale

Advantages and disadvantages of the simplified models to evaluate the seismic performance of steel storage tanks

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ACADEMIC YEAR 2023-2024

Turin, 12/11/2024

Acknowledgements

At the end of this work, I would like to thank all those who participated in its realization. First, I would like to warmly thank my supervisor Mrs. SURACE CECILIA for proposing this thesis to me, for taking the time and effort to help me and her advice during all the stages of this work. I would like to extend my sincere appreciation to my external supervisor VASQUEZ MUNOZ LUZ ELIZABETH for her valuable suggestions, her mentorship has added depth to my understanding of the subject matter, contributing significantly to the overall refinement of this thesis.

I am grateful to my family for their constant encouragement, understanding and support during the hard time of this academic endeavor.

Abstract

Aboveground vertical cylindrical steel storage tanks are critical structures used for storing various types of liquids, some of which may be toxic or flammable. These tanks are susceptible to a range of natural events, including wind and earthquakes. The thesis provides a comprehensive understanding of performance and seismic response of aboveground steel storage tanks with uniformly supported flat bottoms. It emphasizes the crucial need for special attention to the tank design and resilience to ensure safety, especially in the face of potentially catastrophic events such as earthquakes. The research delves into the different failure modes experienced by these tanks during ground shaking, including elephant's foot buckling, diamond-shaped wall buckling, base plate failure, anchor bolts failure, roof damage, and piping connection failure.

The seismic behavior of storage tanks is complex, involving hydrodynamic pressure from the oscillating liquid. This pressure creates an overturning moment at the tank bottom, leading to potential buckling. Sloshing of the liquid near the top of the tank can cause severe damage, particularly in roofed tanks with insufficient freeboard or floating roofs. Unanchored tanks are vulnerable to base uplift, resulting in substantial plastic deformation and potential fracture or fatigue failure.

Various simplified models, including the Housner model, Veletsos model, Yang model, Wozniak and Mitchell model, Haroun and Housner model, and Malhotra model, have been developed to analyze the seismic response of steel storage tanks. These models aim to capture the complex interactions between the liquid, tank walls, and foundation, providing insights into the tank's behavior during earthquakes.

It is of paramount importance in engineering to understand the dynamic responses of these structures under a strong seismic excitation to mitigate the risk of catastrophic collapse and potential spillage. Such incidents could lead to significant socio-economic and environmental consequences. Storage tanks behavior during ground acceleration is of great interest because of the complexity of its response.

Consequently, this topic has attracted the attention of numerous researchers over the past decades. The objective of this thesis is to provide a concise overview of some of the most utilized simplified models, along with their pros and cons, for assessing the seismic behavior of steel storage tanks under seismic excitation.

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Preface

Steel storage tanks have been an integral part of various industries, including oil and gas, petrochemicals, and energy production. These tanks play a crucial role in handling a wide variety of liquids in large quantities, such as refined petroleum products, water, and other liquid substances. However, these ground-supported steel storage tanks are vulnerable to various natural phenomena like wind, snow, and notably earthquakes. The forces exerted by these events present significant challenges to the tanks' structural integrity, potentially leading to structural failure and disruption in industrial processes. Among these, seismic loads pose the most substantial threat to the structural integrity and safety of storage tanks.

Tank failure can lead to catastrophic consequences, including uncontrollable fires if the water supply is cut off, explosion risks, and pollution due to the spillage of toxic chemicals. Such incidents could result in the disruption of the supply of essential products and energy resources which may lead to substantial socioeconomic consequences.

Therefore, addressing the seismic vulnerability of storage tanks is imperative to mitigate these risks and protect human life, property, and the environment.

Implementing robust seismic design standards and integrating advanced structural engineering solutions are vital for enhancing the resilience of these tanks against seismic events. This necessitates careful consideration of design factors and adherence to stringent safety protocols.

The aim of this thesis, titled "Advantages and Disadvantages of the Simplified Models to Evaluate the Seismic Performance of Steel Storage Tanks," is to conduct a thorough analysis of the most commonly used simplified models for evaluating the seismic performance of steel storage tanks under seismic loads.

The thesis is structured into six chapters. Chapter 1 lays the foundation with a general introduction to the behavior of these tanks during past earthquakes. Chapter 2 explores the core topic, discussing the most relevant existing simplified models used for evaluating such behavior. Chapter 3 weighs the pros and cons of these chosen models, providing a balanced view of their advantages and disadvantages. Finally, the conclusions bring the thesis to a close by presenting the results obtained from the study and drawing conclusions based on these findings.

By addressing these objectives, this thesis aims to contribute valuable insights into the seismic vulnerability and structural integrity of above-ground cylindrical steel storage tanks, thereby informing strategies for enhancing their resilience and mitigating potential risks.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Steel storage tanks are structures used to store large volumes of liquids substances in many process industries, such as oil refineries and petrochemical plants, particularly those of vertical cylindrical configuration. These are commonly used due to their ease of fabrication, erection, and maintenance. These tanks often contain toxic, flammable, and explosive substances or fuel that are crucial for recovery after a catastrophic event. Damage to these facilities poses significant risks, extending beyond material loss to the potential loss of human life and long-lasting environmental impact. Understanding how these tanks interact with their foundation and containments during earthquakes is a complex analytical task. [1]

The specifications outlined by the facility owner can impact the selection of a liquid storage tank and the nature of the stored substance often leads to choosing a suitable tank type. We can classify storage tanks in numerous ways. A common classification is based on their position concerning the ground level: they can be either above or below ground (Figures 1-1 and 1-2), which may also differ based on whether the tank's base plate rests on the ground or a supporting structure and whether it is anchored or unanchored (Figures 1-3 and 1-4).

This thesis is primarily concerned with aboveground tanks that have uniformly supported flat bottoms. Most tanks possess a vertical cylindrical body, the cylinder is constructed from curved plates that are welded together. The walls can either be the same thickness all the way up or have different thicknesses at different heights. These structures offer several benefits: they are less complex to construct, can accommodate larger volumes, and are more economical. Aboveground storage tanks are often preferred because of their ease of inspection, maintenance, and cleaning access. Another approach to categorizing storage tanks is by the operating pressure. Tanks that operate at a pressure slightly above atmospheric pressure are known as atmospheric tanks. On the other hand, tanks designed to contain gases or liquids at a significantly different from the ambient pressure are termed pressure vessels or high-pressure tanks. [2]

Figure 1-1: Example of above-ground storage tank (Courtesy of SIS GmbH)

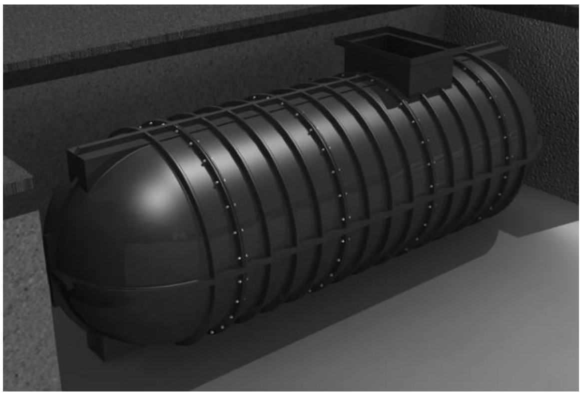


Figure 1-2: Example of belowground storage tank (Courtesy of D&H Group

Figure 1-3: Example of anchor (Courtesy Vathi & Karamanos)

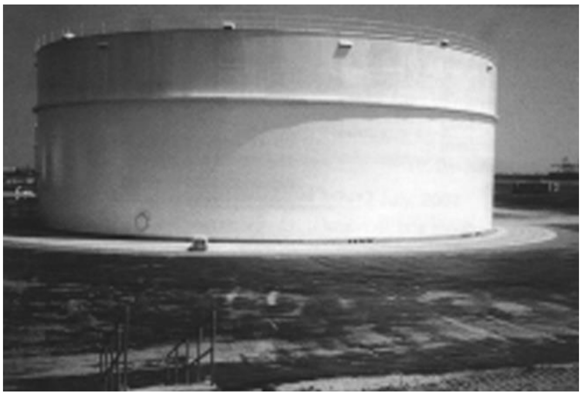


Figure 1-4: Example of unanchored storage tank (Courtesy of D&H Group)

In some cases, steel storage tanks, especially those of a vertical cylindrical configuration, may require a top closure and can be differentiated in numerous ways, with one significant method being based on their roof designs. Fixed-roof tanks are distinguished by a shallow cone roof deck that mimics a flat surface, typically constructed from steel plates, offering a robust and durable cover for the tank.

Conical roof tanks, the most used for storing large volumes of fluid, are designed with roof rafters and support columns for additional stability. However, these features may not be present in tanks with minimal diameters.

Umbrella-roof tanks bear a striking resemblance to cone-roof tanks. However, with a critical difference - the roof is shaped like an umbrella, eliminating the need for support columns extending to the bottom of the tank and offering a clear internal space.

Dome-roof tanks feature a roof that mirrors a spherical surface, providing a distinct aesthetic and functional advantage with enhanced strength and resistance to external pressures.

Floating-roof tanks are equipped with a cover that floats on the surface of the liquid stored within, minimizing evaporation losses, and making an excellent choice for storing volatile liquids. The floating roof adjusts its height with the liquid level, thereby reducing vapor space above the liquid level and decreasing evaporation. [3]

Given the crucial role of liquid storage tanks in various industries, it is imperative to understand their vulnerability to natural loads such as wind and earthquakes. This thesis underscores the need for special attention to the design and performance of these tanks under to ensure their resilience and safety. With the potentially catastrophic consequences of tank failure, particularly during earthquakes, and the complex behavior of these structures during earthquakes, researchers have significantly increased interest in investigating the seismic response of ground-supported steel storage tanks.

1.2 Examples of past disastrous earthquakes

During a ground shaking, the tanks can experience different types of failure modes, each contributing to the overall complexity of their behavior. Specifically, the traditional elephant's foot buckling is the most often seen collapse mechanism in aboveground steel storage tanks, the tank wall's diamond-shaped buckling close to the base, failure of base plate (uplifting), anchor bolts failure, roof damage and piping connection failure are other well-known tank failure scenarios such as failures of base anchoring in the case of anchored tank. [4]

The 1999 Kocaeli Earthquake in Turkey, with a magnitude of 7.6, had a significant impact on industrial facilities, particularly the Tüpras refinery. The seismic event led to substantial damage, with approximately 20 tanks in the refinery farm being damaged or destroyed by fire.

A major fire was ignited in the tanks that contained naphtha, the sloshing motion of the containment generated by the earthquake caused the floating roof to rub against the walls and created sparks, instantly igniting the liquid. The fire then spread to the crude oil tanks, damaging 30 of the 45 tanks. Furthermore, the intense heat from the burning tanks caused thermal buckling of a fixed roof tank (Figures 1-5 and 1-6). In addition to economic losses, large quantities of toxic materials were released into the environment. [5]

Figure 1-5: Tank farm with some tanks destroyed by fire in Tüpras refinery [6]

Figure 1-6: Thermal buckling due to heat radiation [6]

Three notable earthquakes in Japan offer important new information for the investigation of behavior of storage tanks during seismic events. The Showa Oil refinery suffered significant damage because of the 1964 Niigata Earthquake. In particular, the combustible vapors ignited in 12 tanks as a result of mechanical shoe seals colliding with the tank wall.

The 1978 Miyagi Earthquake demonstrated another form of damage. The seismic activity caused an uplift of the bottom plate of the tanks. The uplift caused a significant plastic strain in the shell-bottom joint weld, which resulted in a catastrophic failure. The tank contents subsequently spilled into the port (Figure 1-8). However, unlike the Niigata incident, no fire ensued.

The 1995 Kobe Earthquake presented yet another pattern of damage. Tanks exhibited diamond-shaped and “elephant foot” buckling of the tank shell (Figure 1-7). Additionally, some tanks were inclined due to soil liquefaction. Despite these deformations, no leaks or fires were reported. [7]

Figure 1-7: Diamond-Shaped Buckling (Courtesy of N R I of Fire and Disaster, Japan)

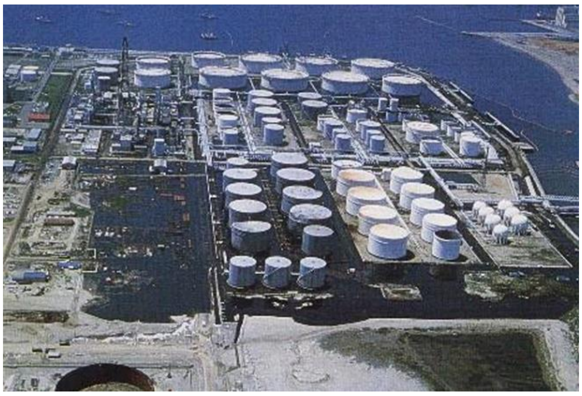


Figure 1-8: Oil spillage to the port [7]

In the USA, California, a state that is known for its high seismic activity, steel storage tanks experienced significant damage during the May 1983 Coalinga Earthquake. Typical damage observed across various tank sites include Elephant’s Foot Buckling at the base of the tank. Riveted joint tanks suffered severe damage with buckled top courses and ripped joints, leading to extensive oil spills. Tanks with floating roofs showed damage to roof pontoons. Broad tanks experienced a rupture in the bottom plate due to the uplift of the base plate. Other sites reported damage to piping connections and punctures due to internal frame impact.

These damages, while less catastrophic than complete structural failure, can still lead to significant operational disruptions, financial losses, and environmental impact. [4]

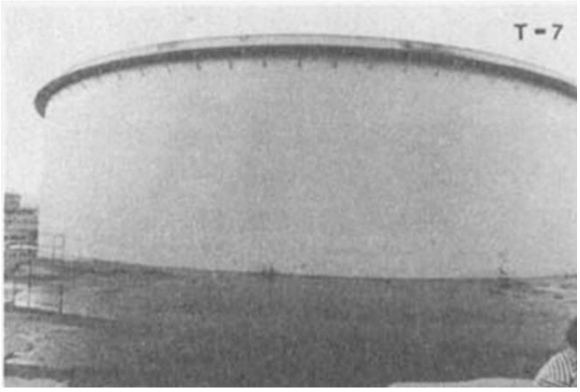


Figure 1-9: Oil spillage due to bottom plate rupture [4]

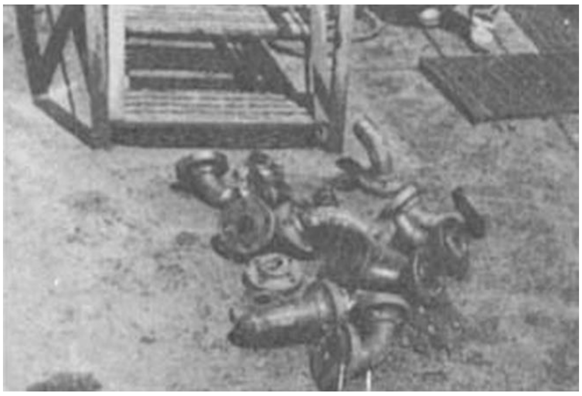


Figure 1-10: Damage to piping connections [4]

1.3 Assessment of damage to steel storage tanks due to earthquakes

Aboveground steel storage tanks can suffer minor to moderate damage in certain circumstances depending on the intensity of the earthquake and the tanks configuration. In the case of unanchored broad tanks, the overturning moment can cause a partial uplifting of the base plate from the foundation, and the consequences can lead to damage to any connected piping. One of the most common forms of damage is the buckling of the tank wall, which can take several forms. Furthermore, accessories surrounding the tank, such as the fire-fighting system, inlet/outlet piping and maintenance stairs, are also vulnerable to damage. [8]

1.3.1 Buckling at the Bottom of Tank Wall

The behavior of a storage tank is relatively straightforward under static condition. However, its dynamic response during seismic loading is quite complex. When subjected to seismic excitation, the liquid inside the tank begins to oscillate, creating hydrodynamic pressure. This pressure generates an overturning moment at the tank bottom, which can lead to the formation of the Elephant Foot Buckling due to the increase on the axial stress in the lower course of the tank. [9]

This Elephant Foot Buckling (EFB) is an elastic-plastic buckling, characterized by an outward bulge near the base of the tank (Figure 1-11). EFB is a critical failure mode in storage tank, even though the tank is not completely collapsed, typically formed due to the uplift of the base plate. This phenomenon results from the combined effects of tensile hoop stress and compressive meridional stress. When these stresses exceed the critical threshold, EFB occurs. [10] However, the formation of the EFB is highly sensitive to initial shell imperfections, but this sensitivity decreases with internal pressure. At low levels of internal pressure, the shell fails through elastic buckling, but with a notable increase in strength. As internal pressure increases, the strength gains are smaller, and the buckling becomes more axisymmetric and less affected by initial imperfections. [11] However, if an EFB forms around a nozzle or manhole, it is more likely to cause a leak. [12]

Another observed type of buckling is the Diamond-Shaped Buckling (DSB), which is less common than EFB. DSB is an elastic deformation characterized by a diamond-like pattern on the bottom course of the tank, occurs relatively at low hoop stress levels and is highly sensitive to internal pressure and initial imperfection in the tank shell. [13] DSB is typically observed in slender stainless tanks, the ratio of the radius to shell thickness is low, most slender tall tanks are anchored to the foundation. [14] Figure 1-12 shows such a buckling.

Figure 1-11: Elephant's foot buckling of the lower of the tank [11]

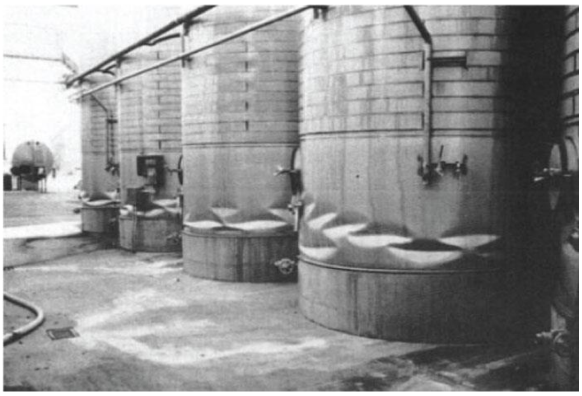


Figure 1-12: Diamond-shaped buckling [15]

1.3.2 Buckling at the top of tank and roof damage

Sloshing refers to the movement of the liquid near the top of the tank due to the excitation of the convective mass, which is characterized by a long period (6 to 10 seconds). In roofed tanks with insufficient freeboard or tanks with floating roofs, this sloshing can cause severe damage due to the interaction between the upper part of the tank and the sloshing liquid.

This behavior can be categorized into three types based on the intensity of the oscillations and the shape of the liquid's surface.

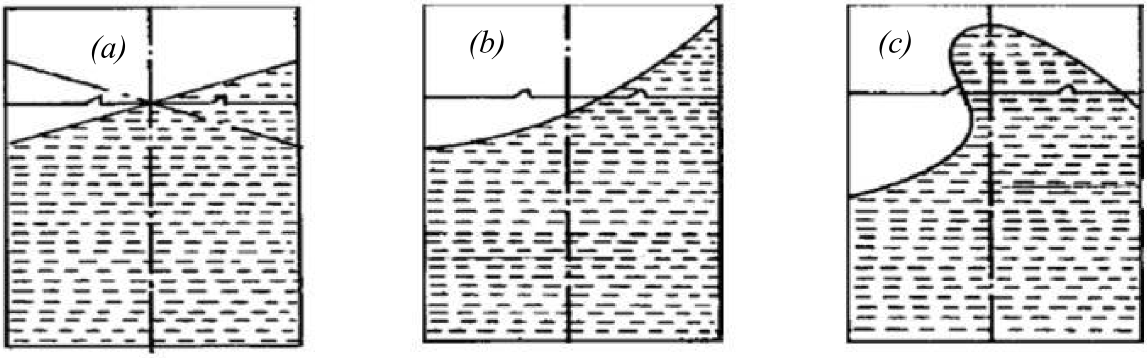


Figure 1-13: Different types of sloshing behavior of the free-liquid surface of a tank excited by horizontal acceleration.[16]

Linear Sloshing (Case a): In this scenario, the liquid experiences minor oscillations, and its surface remains flat. This is a perfectly linear

Weakly Nonlinear Sloshing (Case b): Here, the liquid undergoes oscillations of varying magnitude, and its surface is no longer flat.

Nonlinear Sloshing (Case c): In this case, the liquid exhibits a strongly nonlinear motion at the surface, primarily due to rapid velocity changes associated with hydrodynamic pressure impacts near the free liquid surface. This highly nonlinear fluid behavior necessitates the use of sophisticated computational methods.

In the case of nonlinear waves, deriving the sloshing phenomenon using an analytical method is challenging. Therefore, numerical simulation becomes essential for investigating parameters such as sloshing, maximum height, and periods of resonance. [17]

In the case of aboveground steel storage tanks equipped with a floating roof, the floating roof is designed to rise and fall with the liquid level, minimizing vapor space and reducing fire risk. However, sloshing can cause damage to the floating roof, lead to wear and tear on the roof's seals and joints, compromising its ability to effectively contain the tank's contents. In more severe cases, the roof can sink into the tank, due to mechanical failure. This sinking can render the floating roof inoperable, leading to increased vapor emissions and a higher risk of fire and explosion. Roof damage can also result in spilling of the tank's contents, posing environmental and safety hazards. [18]

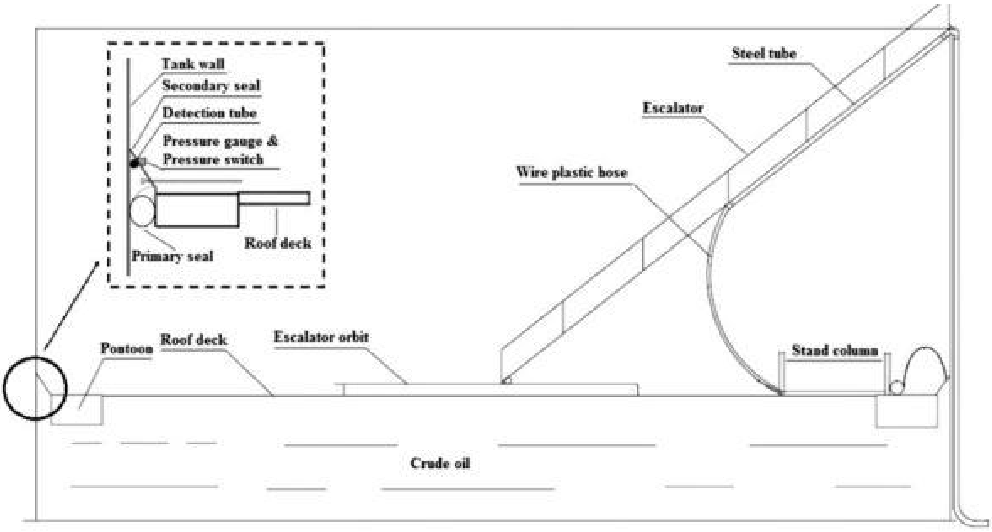


Figure 1-14: Floating roof with sealing system.[19]

1.3.3 Base plate uplifting

The seismic response of aboveground vertical cylindrical steel storage tanks is a complex phenomenon. These tanks, often constructed without anchoring, are in simple contact with the foundation. When subjected to strong seismic loading, they may experience a base uplifting mechanism, which is a highly nonlinear phenomenon where a portion of the base plate is uplifted and separated from the support foundation. [20]

The base uplift can lead to substantial plastic deformation in the vicinity of the welded connection between the tank shell and the bottom plate, posing a risk of fracture or fatigue failure of the welded joint under repeated cycles of the uplift. Since the base plate is held down by the hydrostatic pressure of the tank contents, the base weld is subject to high stresses and fracture may result. Additionally, the tank's uplift can cause an increase in compressive meridional stress and hoop stress in the tank walls, which may result in elephant foot buckling damage, tearing, and failure of pipe connections. [21]

However, tanks resting on a flexible soil foundation do not experience a significant increase in axial compressive stress in the tank wall, instead, lard foundation penetration may occur. Consequently, tanks that are resting on flexible foundation are less susceptible to EFB but more prone to uneven foundation settlement. [22]

Overall, the seismic performance of unanchored liquid storage tanks is dominated by the uplift phenomenon, this response underscores the need for careful consideration in the design and assessment of such tanks to mitigate potential structural failures during seismic events.

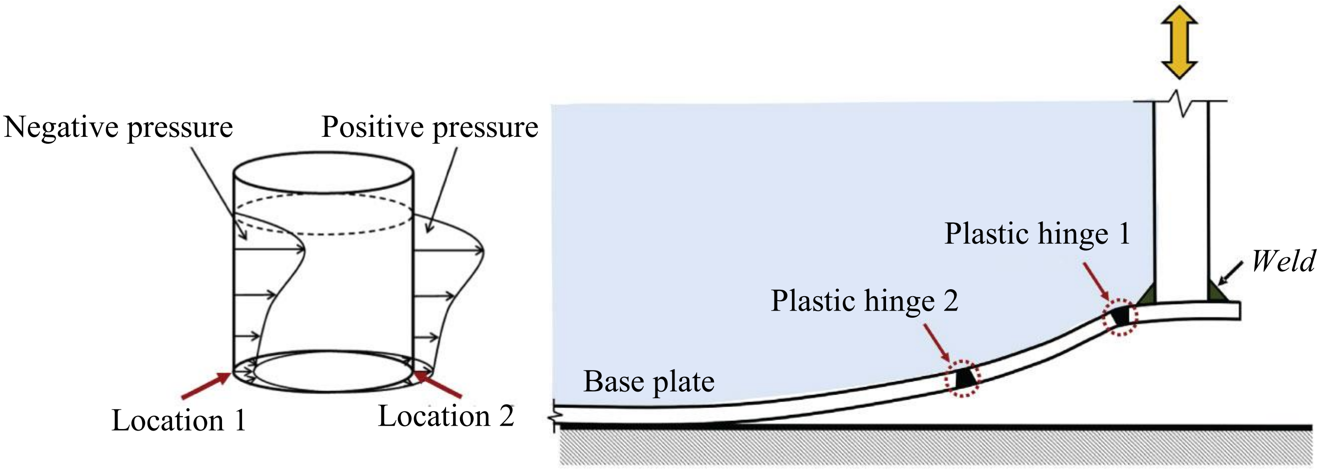


Figure 1-15: (right) base plate uplift phenomena in unanchored tanks, (left) the locations where plastic hinges develop [21]

1.3.4 Tank sliding and piping system failure

When unanchored or not adequately anchored and subjected to strong ground motion, the tank is susceptible to horizontal and vertical movements; these movements can lead to several types of damage. A tank's horizontal (sliding) movement can lead to breaks in inlet and outlet piping connections that are not designed to accommodate such motions. This inability to absorb the Tank's movements due to insufficient flexibility is a common cause of product loss from storage tanks during earthquakes. This type of damage can be effectively mitigated by implementing flexible connections, a solution that ensures the piping systems remain intact and functional, even during the Tank's movement. [23]

1.3.5 Anchorage Failure

Anchorage failure in steel storage tanks during earthquakes is very important because it can cause serious damage to the structure. The rocking motion induced by the overturning moment during an earthquake generates tensile forces in these anchor bolts. This motion can lead to significant stress, potentially causing pulling forces that can rupture the tank wall. Additionally, some tanks experience weld ruptures at the joint between the bottom course and the annular plate, which is integral to the anchorage system. [24]

The figures below highlights anchorage failure in storage tanks subjected to strong seismic excitation. Frequently, excessive inelastic strain demands were imposed on the anchor bolts, resulting in their fracture or pull-out from the concrete pads. [25]

Figure 1-16: anchorage failure of a tank during Hanshin-Awaji earthquake [26]

Figure 1-17: Anchor rod failure during Peru earthquake 1995 [27]

1.3.6 Foundation Settlement

The performance of cylindrical storage tanks also depends on the quality and stability of their foundation. The uneven settlement of a liquid storage tank during an earthquake can result from several factors. One primary cause is the heterogeneous nature of the foundation of the soil beneath the tank. Variations in soil composition and density can lead to differential settlement, where some foundation areas settle more than others.

Uneven settlement can lead to a tilt or differential settlement of the base, which imparts additional stress to the tank wall, which can cause the tank shell to buckle. [2]

However, the foundation flexibility can reduce the compressive stress developed at the tank's base. [4]

1.4 Damage States for Liquid Storage Tanks

In assessing the seismic damage of liquid storage tanks, it is essential to define various damage states based on the severity of the damage. According to studies [28], four distinct levels of damage can be identified: Level 0, indicating no damage; Level 1, representing minor (non-severe) damage; Level 2, indicating major damage without loss of containment; and Level 3, signifying major damage with loss of containment.

A risk study on Natech accidents, which are industrial accidents triggered by natural events such as earthquakes, was conducted by Krausmann et al. (2011) [29]. This study focuses on the ranking of seismic damage commonly observed in reservoirs based on severity. The seismic damage is categorized into two groups: whether there was a liquid spill or not. Such classifications and studies are vital for improving safety measures and mitigating the risks associated with seismic events affecting liquid storage tanks.

Tank failure without any leakage	
Severity	Failure mode
Minor	EFB Anchors elongation (tensile) Sloshing damage
Moderate	Anchor failure Well connection failure Roof damage due to sloshing Failure of supporting columns

Table: Different failure modes without contents spill [29]

Tank failure with leakage	
Severity	
Minor	Failure of inlet/outlet piping connections
Moderate	Spill from tank top
Catastrophic	Tank collapse and tilting

Table: Different failure modes with contents spill [29]

1.5 Conclusion

In conclusion, this chapter has examined the critical aspects of the seismic response of steel storage tanks, emphasizing the various failure mechanisms and damage states that these tanks may experience during earthquakes. Steel storage tanks, particularly those with vertical cylindrical configurations, are crucial for storing large volumes of liquids in industries such as petrochemical and oil refining, where their structural integrity is vital to both operational safety and environmental protection.

The review of past earthquake case studies has shown the devastating consequences of tank failure. The observed damage states, such as elephant foot buckling, diamond-shaped buckling, roof damage, piping connection failure, and base plate uplifting, highlight the critical need for cautious design and assessment to ensure the tanks' resilience and safety. Consequently, this detailed analysis underscores the necessity for implementing robust safety measures and innovative design approaches to mitigate the destructive effects of earthquakes on above-ground steel storage tanks.

CHAPTER 2

DESCRIPTION OF THE SIMPLIFIED MODELS

2.1 Introduction

Early research on the response behavior of steel storage tanks subjected to horizontal ground motion, predominantly focused on anchored tank with rigid walls, and resting on rigid support foundation. Extensive investigations have been conducted on evaluating the seismic response of aboveground steel storage tanks. Analyzing the seismic behavior of these structures is complex due to different interactions that take place between the liquid, the tank walls and the foundation. Horizontal ground acceleration generates both impulsive and convective hydrodynamic pressures. Similarly, vertical ground acceleration also induces both impulsive and convective hydrodynamic pressures. The determination of the hydrodynamic forces is a crucial step in the seismic design of structures such as storage tanks.

During seismic events, the liquid within a storage tank plays an essential role, especially since these tanks can be full or empty at the moment of the seismic event. The ground accelerations induce inertial forces on the liquid which interacts with the tank walls, leading to overpressures or hydrodynamic depressions along the walls and at its base.

Research on the behavior of liquid storage tanks and their interactions have led to the development of simplified models. These models are designed to simulate the dynamics of fluid movement within the tanks and the fluid-structure-foundation interactions. One of the first to provide a solution to this problem was Jacobsen (1949) [30], who determined the hydrodynamic pressures on a rigid cylindrical tank, anchored to the rigid foundation and subjected to horizontal acceleration using a simplified analytical method.

In the late 1950s and early 1960s, Housner published two works, Housner (1957) [31] and Housner (1963) [32], in which he formulated the simplified analytical method, which is still employed today by practical engineers and current tank seismic design code for estimating the response of a cylindrical liquid storage tank under seismic excitation. He analytically solved

Laplace’s equation for the fundamental mode of rectangular and cylindrical rigid tanks resting on rigid foundations and subjected to horizontal excitation. His study concluded that the hydrodynamic pressure of the liquid in a rigid tank can be divided into two components: an impulsive component and a convective component.

Following the development of Housner’s model, a significant volume of research was conducted, leading to the creation of various simplified models. These studies were carried out by many researchers, including Westergrade, Haroun, Velestos, and Malhotra, among others. In this chapter, we will present the developed simplified models for the seismic analysis of liquid storage tanks.

2.2 Existing Models for Evaluating Seismic Performance

2.2.1 Housner Model (Mass-Spring Model)

Developed by George Housner, it is a simple and widely adopted mechanical model for analyzing the seismic response of liquid storage tanks under a ground excitation. The toral response of the liquid withing a storage tank can be modeled as a mechanical mass-spring system. This model uses the decomposition of hydrodynamic pressure into impulsive and convective pressure. The upper portion of the liquid has a sloshing motion has a long vibration period of 6 to 10 seconds, while the rest of the fluid that moves together with the tank, (i.e. impulsive motion) has a shorter period of 0.1 to 0.2 seconds. [33]. The primary objective of this model is to individually calculate the seismic responses of the SDGF systems. Once these responses are determined, they are combined to obtain the overall tank base shear and overturning moment.

Impulsive pressures, which are directly associated with the inertial forces generated by the impulsive movements of the tank walls, are directly proportional to the acceleration of these walls. [31] The proportion of the liquid mass participating in the convective motion is contingent upon the ratio of the free surface height to the tank diameter of the tank. [16]

Impulsive pressure is represented by a lumped mass that is rigidly attached to the tank walls through a rigid link, its mass $\boldsymbol{m_i}$ and height $\boldsymbol{h_i}$ are defined accordingly to simulate the same lateral forces and overturning moment as the impulsive liquid pressure, this impulsive mass moves in unison with the tank wall, contributing primarily to the hydrodynamic pressure on the tank wall. In contrast, convective pressure is illustrated by a series of masses connected to the walls by springs elastically attached to the tank wall. These masses decrease in size to represent different fundamental sloshing modes. The masses are fixed at levels above the base plate, corresponding to the height of their respective centers of pressure. The components were subsequently modeled as an equivalent single degree of freedom (SDOF) oscillators. Figure 2-1 shows the mechanical model of Housner.

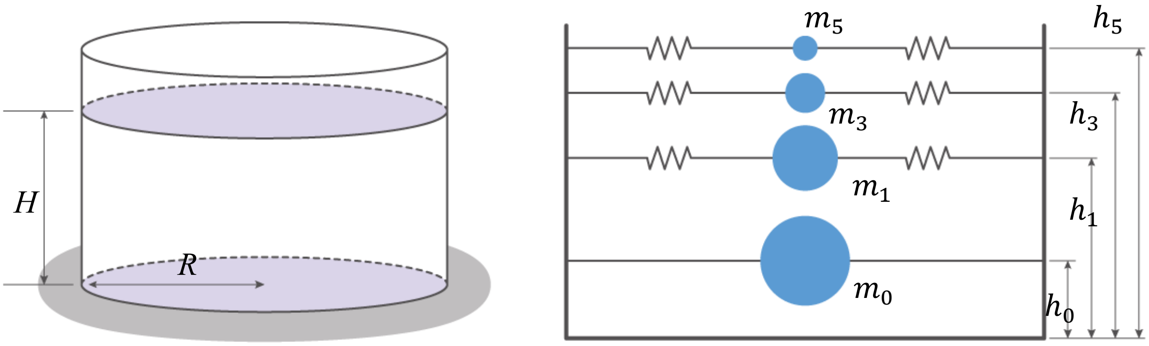


Figure 2-1: Housner Model (Housner 1957)

As illustrated in the figure, only the odd-numbered convective masses are present, which correspond to the antisymmetric convective modes. The even-numbered symmetrical convective modes are absent due to the rigidity of the tank wall; their participation factor is zero.

Moreover, the mass attributed to the first convective mode significantly outweighs the other modes ($\boldsymbol{m_3}$ and $\boldsymbol{m_5}$), thereby making it the predominant mode in the convective response [34]. This dominance of the first convective mode is also emphasized in Housner's 1963 paper. Housner justified the retention of only the first convective mode in his model by highlighting its significant role in response to seismic excitation.

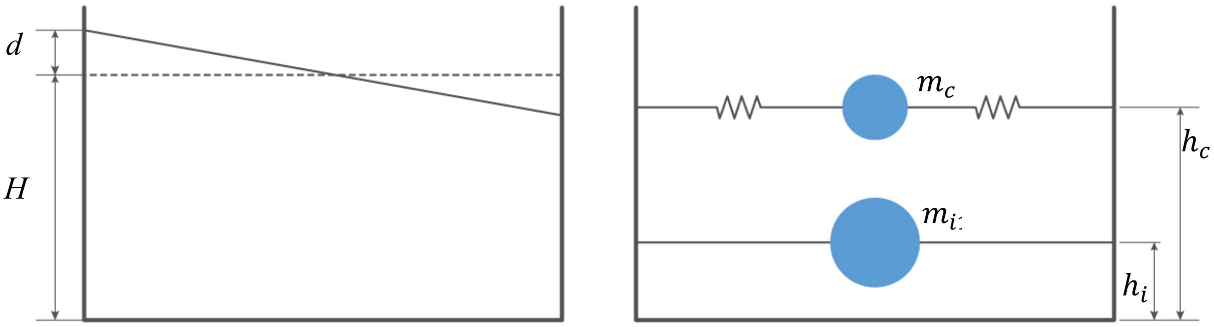
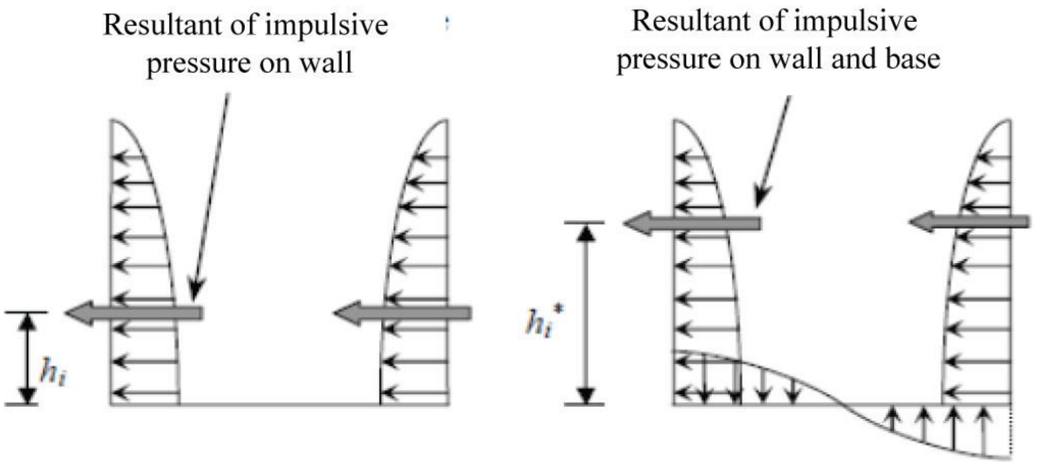


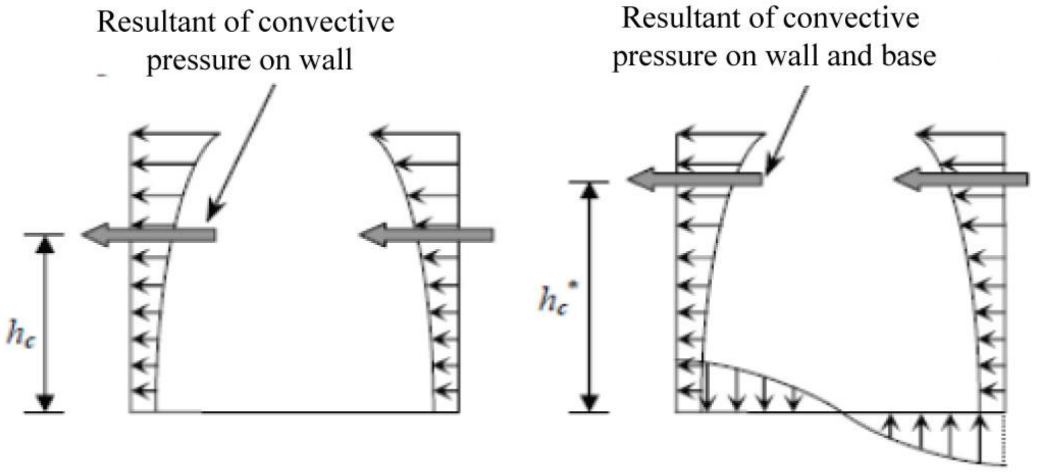
Figure 2-2: Simplified Housner Model (Housner 1963)

Figure above on left shows the free surface of the tank deformation of the first convective mode. On the right it shows the simplified model using mass-spring for impulsive and convective modes. The convective mode characterized by a convective mass denoted as $\boldsymbol{m_c}$ and an associated stiffness $\boldsymbol{k_c}$, the spring stiffness $\boldsymbol{k_c}$ is calculated so that the frequency of the mass-spring system matches the fundamental vibration frequency f the convective response. The convective mass $\boldsymbol{m_c}$ and its position $\boldsymbol{h_c}$ relative to the tank base are determined to ensure that the lateral force and overturning moment exerted by the mechanical oscillator at the tank base match those of the oscillating convective mode. The aim of the model is to calculate the seismic responses of the Single Degree of Freedom (SDOF) systems independently. The maximum lateral base shear and overturning moment at the tank base are derived by summing the contributions from both the impulsive and convective response modes.



(a) Impulsive pressure on wall

(b) Impulsive pressure on wall and base



(c) Convective pressure on wall

(d) Convective pressure on wall and base

Figure 2-3: Different hydrodynamic pressures induced by a ground excitation on tank [35]

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2.2.2 Veletsos Model for Flexible Tanks

During strong earthquake events, such as those in Alaska, liquid storage tanks often exhibited poor performance, prompting researchers to develop new procedures for seismic analysis that account for the flexibility of the tank wall. These procedures are inherently more complex than those for rigid tanks due to the simultaneous dynamic response of the liquid and the tank wall's motion.

Previous analytical studies primarily considered tanks as rigid, focusing on the dynamic behavior of the contained liquid. However, significant post-earthquake damage revealed that this rigid assumption could lead to an underestimation of the seismic response. This highlighted the importance of considering the flexibility of the storage tank and its interaction with the liquid. [36]

When accounting for the flexibility of the tank wall, the impulsive portion can experience accelerations significantly higher than the peak ground acceleration (PGA). Consequently, the calculated base shear and overturning moment assuming a rigid tank may yield non-conservative results. In contrast, the convective portion, or sloshing response, remains unaffected by the wall's flexibility. [37]

Veletsos proposed one of the first analytical methods that included tank wall flexibility in 1974. [38] Veletsos introduced a straightforward method for analyzing and evaluating the dynamic response of storage tanks subjected to horizontal ground motion. This method does not consider convective forces, which must be determined separately using Housner's procedure for rigid tanks. The tank system is treated as a single degree of freedom. Several assumptions underpin this approach: the tank's cylindrical cross-section remains circular throughout the analysis, the tank deflects in a predetermined configuration at any given time, and the ratio of the height of the liquid to the tank's radius is less than 1.2

2.2.3 Yang Model for Flexible Tanks

Yang in 1976 [39], made significant contributions to the understanding of fluid-structure interactions in storage tanks by incorporating tank wall flexibility into his studies. He modeled the tank as a beam, which undergoes various shape modes under dynamic loading. Yang's approach included several key assumptions: the tank's cross-section remained circular, the deflection exhibited a specific height-wise distribution, and only the impulsive mode was considered, as the convective mode was unaffected by tank wall flexibility. This model, represented as a single degree of freedom system where the cross-section retains its shape, allows for a focused analysis of the impulsive pressure response. The mathematical formulations can be found in Yang's original document, which provides analytical functions for critical parameters such as maximum hydrodynamic pressure on the tank wall, overturning moments, and maximum base shear resulting from this hydrodynamic pressure. The results reveal notable differences when compared to scenarios involving a rigid tank wall, highlighting the importance of accounting for wall flexibility in seismic design considerations.

2.2.4 Wozniak and Mitchell 1978 (unanchored tanks)

Unanchored tanks, characterized by their bottom plates not being fixed to the foundation, present unique challenges in design and behavior, particularly under dynamic loading conditions. Unlike anchored tanks, which benefit from the stability provided by fixed foundations, unanchored tanks experience significant overturning moments due to hydrodynamic pressures induced by the earthquake, leading to a partial base uplift. This uplift results in nonlinear fluid-shell-soil interactions and an increase in the maximum axial compression forces within the tank wall. Both dynamic tests and static tilt tests have been conducted to understand these dynamics, revealing that the uplift mechanism largely governs the response of these structures.

Wozniak and Mitchell (1978) outlined fundamental principles for designing unanchored tanks. Their uplift model attributes resistance to overturning moments to a fraction of the fluid's weight, using a small deflection theory to calculate the critical width at which the bottom plate loses contact with the ground. This calculation is based on the assumption of two plastic hinges forming at the plate-shell junction and along the uplifted section.

Additionally, Wozniak and Mitchell (1978) developed a quasi-static beam model for the bottom plate of tanks, which considers the bending of the bottom plate while neglecting its membrane action. This model assumes small uplift displacement, minimal uplift length compared to the tank's radius and models the uplifted bottom plate as a series of beams with unit width and constant length along the circumference. The beam rests on a solid foundation and is subjected to uniform loading. At the ultimate state, two plastic hinges form: one at the junction of the tank shell and bottom plate, and another some distance inward from the shell. The model assumes the bottom plate membrane force to be zero and neglects shear force. [40]

2.2.5 Haroun and Housner

Recent advancements in mechanical models for analyzing the response of the tank-fluid system under horizontal excitation have addressed the impact of wall flexibility on the seismic response of storage tanks. Researchers Haroun and Housner developed a model treating the system as a single degree of freedom, dividing the impulsive mass into two components: a rigid impulsive mass, rigidly attached to the tank wall, and a flexible impulsive mass, connected via a spring with an elastic constant k, This approach allows for a precise evaluation of the tank's behavior, providing insights into the dynamic interactions between the fluid and the structure. The tank wall is represented using finite element modeling, while the liquid inside is analyzed as a continuous medium through boundary solution methods. The model accounts for significant coupling of shell and liquid motions primarily in the impulsive response mode. The dynamic response of the tank-liquid system is represented by distinct masses (mc, mf, mr), and their corresponding heights with natural frequencies and damping ratios. These parameters enable the model to accurately replicate the actual behavior of the tank-liquid system [41 – 42]. This model, depicted in Figures 2-4

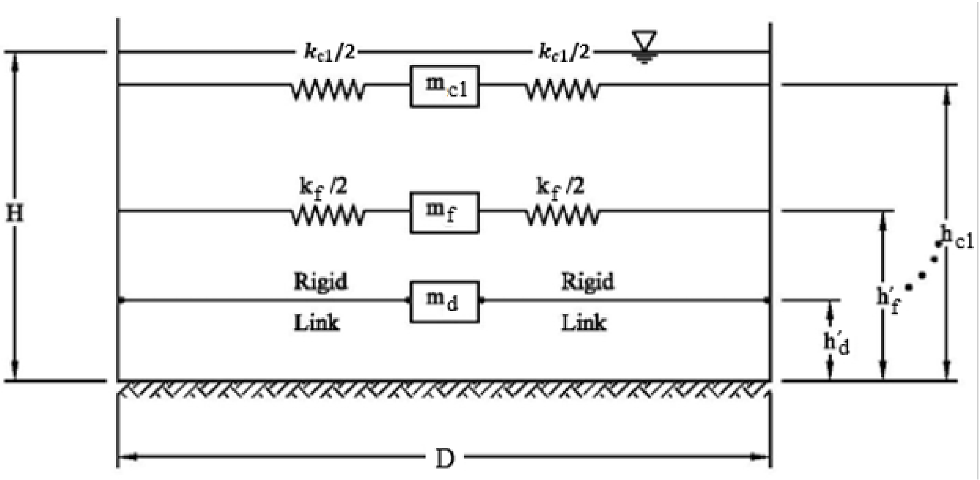

Figure 2-4: Mechanical model for flexible tank [41 – 42].

2.2.6 Velestos Model for Flexible Tanks

In 1984, Velestos developed a procedure to determine the hydrodynamic forces in a tank subjected to acceleration. The tank is anchored to a rigid foundation, and the flexibility of the wall is considered. In this framework, the tank wall is analyzed as a uniform cantilever beam. Assumptions include that the liquid is incompressible, inviscid, and irrotational, the tank is anchored to the foundation, and both the liquid and tank motions are within the linearly elastic range. The tank wall flexibility influences only the impulsive response.

Given the boundary conditions require the tank bottom and liquid velocities to be equal, with the vertical component velocity being zero. The radial velocities of the liquid must match the tank wall, and for flexible tanks, the coupling of the deformable wall and liquid motions is considered. At the liquid's free surface, the impulsive pressure assumes zero hydrodynamic pressure. This analysis is more accurate than that of Housner. [43]

2.2.7 Malhotra model for Base Uplift

Unanchored tanks are commonly used in the field, primarily for economic reasons, yet their behavior presents unique challenges, particularly due to the nonlinear effects associated with bottom plate uplift mechanisms. This complexity has pushed interest among researchers to develop realistic models that can effectively simulate the uplift behavior of these tanks.

Malhotra 1995 [44] presented a method for analyzing the uplift behavior of the base plate of cylindrical tanks under seismic loading addressing both axisymmetric and asymmetric conditions. The partial uplift of the base plate is a highly nonlinear phenomenon driven by several factors, the continuously changing contact area between the plate and foundation, the plastic yielding of the plate material and the membrane action associated with significant deflection of the plate. The problem considered is a circular plate with radius R and uniform thickness simulating the base of an uplifting cylindrical tank resting on a rigid foundation. The plate is subjected to a uniform lateral pressure P due to the hydrostatic pressure of the tank’s contents and a uniform lateral line load W representing the dead weight of the tank wall.

The plate is constrained against radial displacement and rotation by elastic constraints for the axisymmetric case, the relationship between the total upward force and the plates displacement is derived using large deflection plate theory with the corresponding equations presented in Malhotra's paper. In the asymmetric case the overturning moment and rigid-body rotation of the plate boundary are analyzed using a beam model, which represents the uplifted portion of the plate as a series of independent beams.

A comparison of the beam model with the actual model reveals that for moderate uplift the width of the uplifted region predicted by the beam model agrees well with the actual model. However, at very large uplift values discrepancies arise primarily due to differences in the radial membrane stresses computed by the two models.

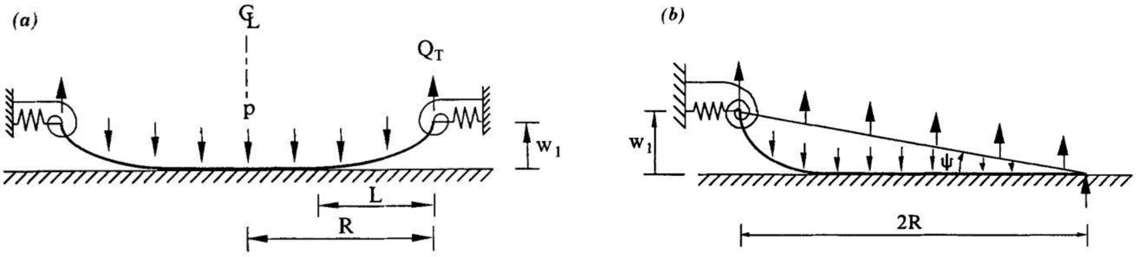

Figure 2-5: uplifting plate (a) Axisymmetric, (b) Asymmetric [44]

2.2.8 Model of Base Isolated Tank

Seismic isolation of liquid storage tanks has been relatively underexplored, with only a limited number of studies addressing this approach. The primary objective of implementing an isolation system is to enhance the tanks' ability to dissipate seismic energy. By isolating the tank from the foundation, the system helps reduce the forces transmitted during an earthquake, thereby minimizing the risk of damage. It has been shown that isolation can significantly reduce hydrodynamic base shears, overturning moments, and axial compressive stress in the tank wall without notably increasing the vertical displacements of the liquid surface due to sloshing. [45] See figure 2-6

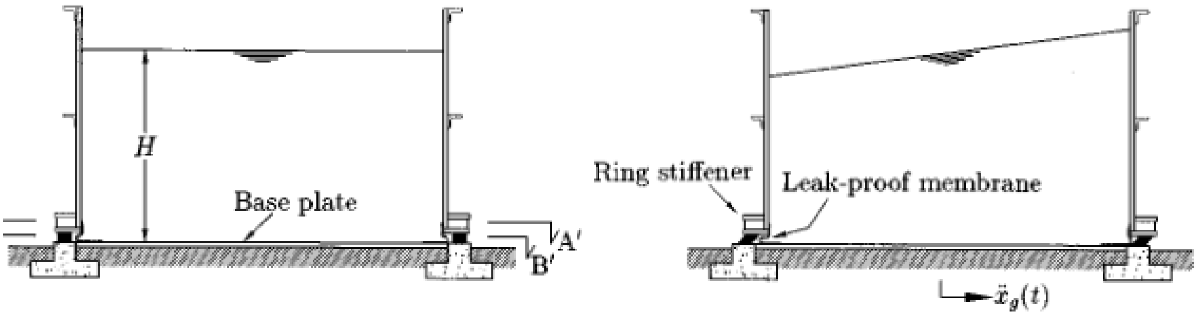

Figure 2-6: Liquid storage tank isolated by proposed method

Malhotra proposed an isolation system for storage tanks, where the tank's base plate rests directly on the soil, and soft rubber bearings are used below the tank wall. This model, depicted in Figure 21, is similar to the fixed base system but includes isolation bearings beneath the tank to achieve a more realistic representation. The analysis parameters for this system can be derived from results published by Haroun and Housner [46].

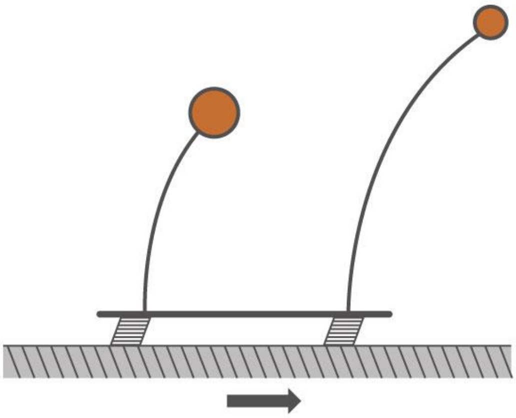

Figure 2-7: Model of base isolated tank

2.2.9 Joystick Model

Bakalis et a1 [47] developed a 3D surrogate model for liquid storage tanks. This model considers all translational components of the ground motion, ensuring its applicability to both anchored and unanchored tanks through static or dynamic analysis methods. Following the approach of Velestos and Tang (1990), the model decomposes the hydrodynamic pressure acting on the tank into impulsive and convective components, though only the impulsive component is considered in the analysis since the convective component does not significantly affect the overall response of the tank.

The proposed "joystick model" is based on a beam-column element that represents the impulsive mass of the tank. The tank itself is supported by a rigid beam-spoke system resting on point or edge springs. To validate the uplift mechanism, a detailed finite element (FE) model using ABAQUS is developed. Results from the FE model and the joystick model, specifically regarding uplift and separation length, show good agreement for a certain aspect ratio of the tanks considered in the analysis. However, the joystick model slightly underestimates the separation length for tanks with low aspect ratio tanks, though the error remains acceptable given the model's simplicity.

In terms of plastic rotation, the joystick model exhibits strong agreement with the EC8 guidelines, with only a 15% difference between the two curves.

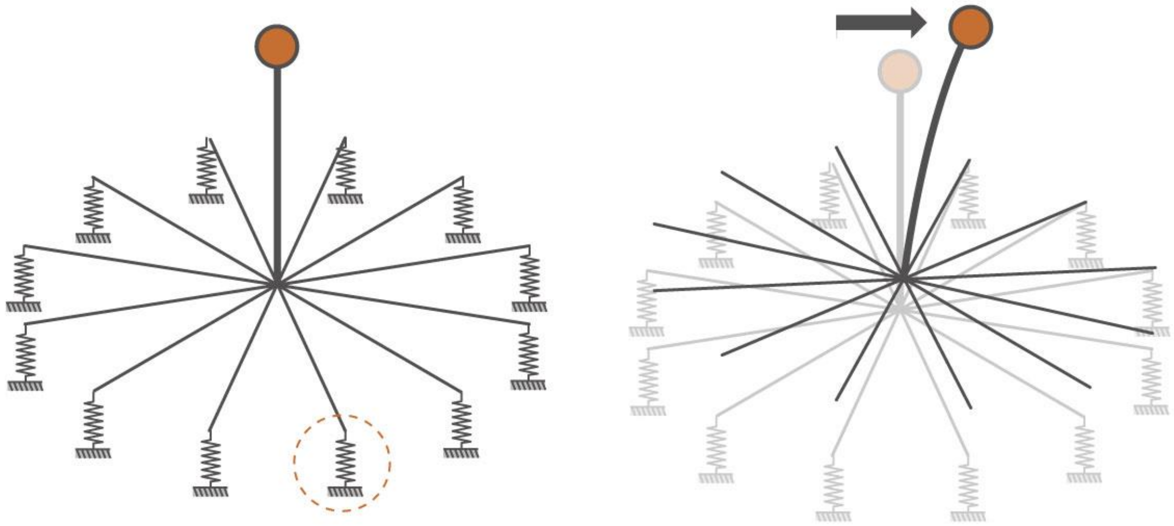

Figure 2-8: Joystick model (left), and its deflected shape (right)

2.2.10 Vathi Model for Base Plate Uplift

In seismic events, one of the primary failure modes observed in steel storage tanks is partial base uplift, which can cause significant structural issues. When the base of the tank experiences an uplift, it can lead to plastic deformation at the connection between the tank shell and the bottom plate, potentially resulting in fractures and the loss of stored liquid.

To address this issue, Maria Vathi et al. [48] developed a simplified model for dynamic analysis of storage tanks, particularly focusing on the effects of uplift.

For anchored tanks, the model considers the tank as a spring-mass system, incorporating the hydrodynamic response of the tank-liquid system, including both convective and impulsive motions of the stored liquid. In the case of unanchored tanks, the same configuration is applied, but with the addition of tank rotation (rocking) due to uplift. This is modeled by adding a rotational spring at the base of the tank to account for the rotational motion induced by uplift forces.

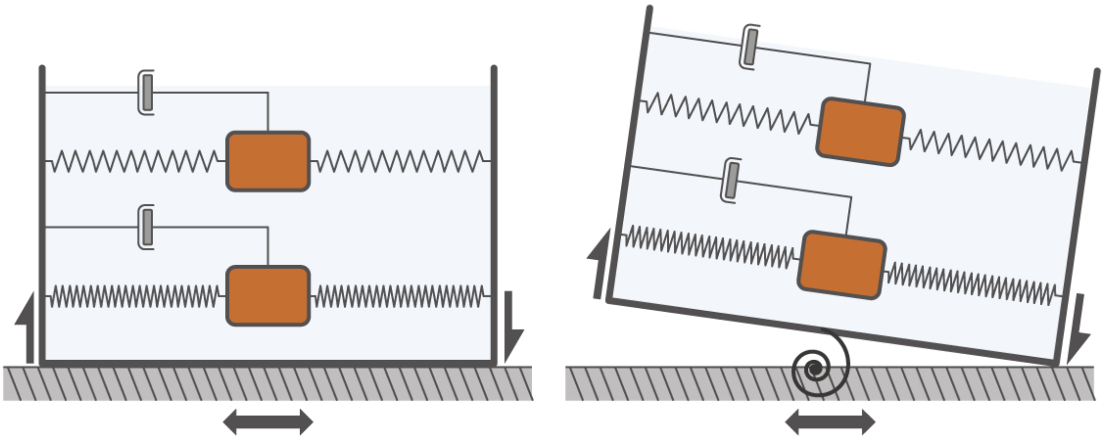

Figure 2-9: simplified model of anchored tank (left), and unanchored tank (right)

The model includes two degrees of freedom: horizontal motion and rotational motion, while the convective motion is considered negligible in influencing the overturning moment.

A nonlinear static analysis is used to calculate key parameters, such as the maximum local strain at the welded connection, with the results supported by a finite element model (FEM) for determining two critical uplifting parameters: the uplifting length and the uplifting size.

2.2.11 3D simplified model

Colombo et al. [49] developed a simplified 3D model for the seismic analysis of unanchored tanks. This model provides accurate estimations of both the rocking resistance of the base plate and the stress distribution on the tank wall. Notably, the simplified nonlinear model proposed in this study can account for the nonlinear moment-rotation relationship and the flexibility of the foundation, making it suitable for the 3D dynamic analysis of storage tanks, allowing for a more accurate representation of the tank's behavior during an earthquake.

The model builds upon a previous model by Malhotra, a key feature of this model is its ability to consider the two horizontal components of ground acceleration. The model's advantages include its reliable estimation of compressive axial stress on the tank wall and its ease implementation in dynamic analysis with earthquake time-histories, making it a practical tool for engineers.

A recent study [50], focused on the damage caused to the shell-base connection due to significant plastic rotation of the base plate. According to current design guidelines, such as EC8 and NZSEE, this rotation is required to be limited to 0.2 radians.

The research highlights the differences in fatigue life capacity between stainless steel and carbon steel tanks. Previous studies predominantly addressed carbon steel tanks. Carbon steel connections withstand a higher number of cycles before crack initiation under small strain amplitudes. Conversely, under large strain amplitudes, stainless steel connections exhibit greater resistance to crack initiation.

Additionally, the study finds that connections with thicker base plates tend to fail after fewer cycles compared to those with thinner base plates. However, this issue can be mitigated by using materials with higher ductility. Enhancing the ductility of the base plates significantly improves the fatigue life of the connections.

2.3 Conclusion

In conclusion, this chapter has provided a comprehensive overview of previous research on the seismic response of steel storage tanks subjected to horizontal ground motion. It discussed various simplified models that are commonly used to simulate the dynamic behavior of aboveground steel tanks during seismic events, emphasizing the complex interactions between the liquid, tank walls, and foundation. Notably, the chapter highlighted widely recognized models, such as the Housner model, which plays a key role in seismic design provisions for storage tanks. Each model considers different aspects of the seismic response. Furthermore, the models examine potential failure modes, including the risk of partial base uplift and early failure of the foundation (EFB) during seismic excitation. Overall, this chapter underscores the importance of understanding these interactions and failure mechanisms to improve the seismic resilience of steel storage tanks.

CHAPTER 3

STRENGTHS AND LIMITATIONS OF CHOSEN MODELS

3.1 Introduction

Steel storage tanks are particularly vulnerable to seismic events, necessitating improvements in safety measures to mitigate the risk of potential damage. Many theoretical and experimental studies have been done recently to address this issue. Building on the analytical findings of researchers such as Veletsos, Haroun, Malhotra, and many others, various simplified models were developed to analyze the responses of both anchored and unanchored tanks. These models have strengths and limitations, which will be discussed in this chapter. While they offer simplified approaches that make it easier to analyze the dynamic responses of storage tanks, certain assumptions and approximations within these models may impact their accuracy.

3.2 Comparative Analysis of Seismic Analysis Models

Housner made several assumptions for this model, only one horizontal acceleration is considered, the tank wall is considered rigid, the liquid within the tank is assumed maintaining contact with the tank's shell, and the base is attached to a rigid foundation, which prevents the base plate from uplifting. However, Experimental studies conducted by Clough et al. (1979) [51], Clough and Niwa (1979) [52], Shih (1981) [53], and Manos and Clough (1982) [54] demonstrated that the axial compressive stress at the shell bottom of unanchored tanks exceeds that of anchored tanks under similar loading conditions. Additionally, Natsiavas and Babcock (1988) [55] highlighted significant differences in hydrodynamic loading between anchored and unanchored tanks, so this may lead to non-conservative analysis of anchored tanks. As the primary concern in the seismic design of liquid storage tanks is the prevention of tank wall buckling. So, to address this, it is essential to monitor the compressive and hoop stresses in the tank wall, particularly at the bottom course, as these stresses are critical to avoiding buckling. Additionally, the determination of liquid sloshing height are vital for establishing the minimum freeboard required between the filling liquid and the roof of the tank.

Housner's method, using a response spectrum, is widely used to determine the seismic response of a storage tank. Until the 1960s, tank wall flexibility was neglected in seismic response analysis, which focused solely on fluid dynamic behavior. It is important to note that this model currently considers only one horizontal direction of base excitation, neglecting the effects of both horizontal and vertical components of ground acceleration.

Various standards and codes for the construction and seismic analysis of cylindrical steel storage tanks, including API 650 [56] and Eurocode 8 [57]. API 650 uses a mechanical model first developed by Housner in 1963 [58], with modifications by Wozniak and Mitchell in 1978. Studies show little difference in the parameters of these models for rigid and flexible tank walls, particularly for impulsive and convective modes.

Eurocode 8, part 4 which covers seismic design and analysis for liquid storage tanks, accepts the mechanical model by Velestos and Yang (1977) [59]

In the context of unanchored tanks, various analytical models have been developed to analyze the nonlinear uplift mechanisms of the base plate. These models have been incorporated into numerous standards and design provisions. Notably, Wozniak and Mitchell (1978) and Clough (1977) introduced quasi-static models that simplify the description of uplift mechanisms, making them suitable for practical design applications

The proposed models by Malhotra offer several advantages, notably its ability to account for the nonlinear effects of both membrane action and material yielding, making it suitable for analyzing the dynamic response of unanchored tanks. Additionally, Malhotra's method considers the effects of load reversals, and the energy dissipation associated with yielding, providing an accurate and efficient approach for analyzing asymmetrically uplifted plates. However, the method has some limitations, primarily its complexity and time-consuming nature, especially when used for dynamic response analyses, where solutions require numerous integration steps. Despite these challenges, the method remains valuable for detailed and accurate analysis of uplift phenomena in cylindrical tanks under seismic loading.

The beam model significantly reduces computational effort, requiring at least an order of magnitude less than the plate model. It offers a more cost-effective and realistic solution by incorporating both material and geometric nonlinearities in the analysis, representing an improvement over the previously proposed method. A major limitation of the beam model is its inability to fully capture the circumferential membrane stresses, which are critical for accurately modeling the behavior of the plate, especially under large uplift. The beam model is most effective when analyzing uplift values that are no greater than 1% of the plate radius.

Sliding Isolation Model is effective in minimizing base shear and the displacement of the tanks. Moreover, these systems can potentially lower costs in areas such as the foundation, anchorage, and materials for the tank, possibly offsetting or even surpassing the additional expenses for isolation bearings, flexible membranes, and base stiffeners.

However, there are some disadvantages. Implementing a flexible membrane between the tank wall and the base plate to prevent spills is complex. Additionally, out-of-round deformation of the tank wall near the base necessitates the use of a stiffener ring. Furthermore, this model only considers the responses of convective and impulsive modes under horizontal accelerations, which may not fully capture all dynamic behaviors during seismic events.

The Joystick Model provides several advantages, including the ability to incorporate anchorage effects, deliver reasonable accuracy with good computational efficiency, and perform 3D analysis of liquid storage tanks subjected to multiple components of ground motion. Additionally, it can be easily implemented using general-purpose structural analysis software like ABAQUS [60]

However, a notable limitation of the joystick model is its inability to address complex hydrodynamic effects and fluid–structure interactions. This omission may lead to minor errors in the calculation of certain parameters, particularly where these interactions are significant.

Model of Vethi, while this simplified model offers several advantages, such as its applicability to nonlinear dynamic analysis and its ability to compute local strain, it also has notable disadvantages. The model's reliance on numerical simulations and finite element models means it requires considerable computational resources and specialized expertise. Moreover, the simplifications made in the model, such as neglecting the flexibility of the tank wall, may not fully capture the intricate behavior of tanks during seismic events, potentially leading to inaccuracies in certain scenarios where more complex interactions occur.

The 3D Model, model also addresses the interaction between the tank and its foundation, considering both the rocking resistance of the liquid-loaded base plate and the hysteretic damping effect. These effects are modeled using elastic nonlinear springs and equivalent rotational linear viscous dampers, respectively.

Furthermore, the model can estimate the contact length between the tank wall perimeter and the foundation during partial uplift, providing crucial insights into the maximum compressive axial stress on the tank wall. This is achieved by estimating the angle of the arc in contact between the tank wall and the foundation during partial base uplift. a key factor in understanding the tank's response to seismic loads.

In conclusion, the proposed model offers reliable estimations of both the rocking resistance of the base plate and the stress distribution on the tank wall, considering the soil-foundation-structure interaction. It also shows good agreement with the results obtained from the finite element model and Malhotra's model. Overall, the simplified nonlinear elastic model offers a reliable and efficient approach for the dynamic analysis of unanchored tanks, particularly in estimating the stress distribution on the tank wall and the interaction with the foundation during seismic events.

However, with advancements in computational capabilities and the increased availability of commercial finite element analysis (FEA) software, numerous researchers have shown a growing interest in this subject. Simplified methodology for risk-targeted seismic performance assessment for the evaluation of unanchored liquid storage tanks, focusing on the elephant foot buckling (EFB) failure mode. Their approach employs a pushover-based analysis to couple the seismic demand, derived from spectral acceleration at the impulsive period, with the limit-state capacity of the tank wall, defined by stress criteria. The analysis is based on a refined 3D finite element (FE) model of the tank, developed using Abaqus Software, which accounts for nonlinearities such as base uplifting and sliding, as well as both horizontal and vertical components of ground motion and the resulting hydrodynamic pressures.

One of the key advantages of this methodology is its computational efficiency, especially compared to dynamic analyses of similarly refined 3D nonlinear tank models. However, the proposed approach has several limitations. Notably, it focuses exclusively on verifying the EFB failure mode, neglects soil-structure interaction effects and assumes a rigid foundation. Additionally, the pushover analysis cannot account for fatigue from cyclic loading, which may affect tank performance under repeated seismic events.

In conclusion, while the methodology offers a promising approach for assessing the seismic performance of tanks, further research is needed to determine its applicability for evaluating other failure modes, such as base uplifting, sliding, and top wall buckling, as well as to incorporate soil-structure interaction and fatigue effects. [61]

3.3 Comclusion

The interaction between the tank and its foundation plays a critical role in determining its dynamic response. The flexibility of both the tank wall and the supporting foundation can significantly influence the overall system response, primarily due to the dominant impulsive response. Understanding these interactions is essential for accurately modeling the dynamic behavior of storage tanks, thereby improving design practices and enhancing structural resilience in seismic events.

CONCLUSIONS

The thesis provides a comprehensive understanding of the performance, and seismic response of aboveground steel storage tanks under seismic excitation. The research delves into the different failure modes experienced by these tanks during past earthquakes, including elephant's foot buckling, diamond-shaped wall buckling, base plate uplifting, anchor bolts failure, roof damage, and piping connection failure.

Dynamic studies on the seismic response of unanchored tanks have highlighted the complexity of their behavior under earthquake loading, because of the complicated interactions between the fluid, the tank shell, and the foundation. The current models available are not fully satisfactory, these models may effectively capture many aspects of tank behavior; however, there is a need for future research to develop more sophisticated finite element models. Such models should incorporate material and geometric nonlinearities to provide a deeper understanding of the complex interactions involved.

Looking towards for future research on the seismic performance of steel storage tanks, potential work could focus on developing advanced models in order to:

1. Investigate the effects of incorporating both horizontal and vertical components of ground motion in the seismic analysis of storage tanks
2. Develop advanced analytical and numerical models that can accurately capture the complex fluid-structure-soil interactions, including the effects of base uplift and sliding, to provide more comprehensive and reliable analysis.
3. Explore the influence of soil-structure interaction on the seismic response of storage tanks, particularly for tanks resting on flexible soil foundations
4. Examine the long-term fatigue behavior of tank-foundation connections under repeated seismic loading cycles, as this can lead to damage and failures

5. Investigate the effectiveness of seismic isolation systems for storage tanks, including the use of base isolation, and expand the understanding of their performance under various seismic loading conditions
6. Conduct further experimental and numerical studies to validate and refine the existing simplified models, ensuring that they can accurately capture the complex nonlinear behavior of storage tanks subjected to seismic excitations.

Another avenue for future investigation could involve the development of simplified methodologies for risk-targeted seismic performance assessment, particularly in evaluating unanchored liquid storage tanks with a focus on possible failure modes This could include exploring innovative analysis techniques, such as pushover-based approaches, to couple seismic demand with the limit-state capacity of tank walls to define stress criteria and enhance the overall understanding of tank behavior during seismic events.

With the advancement in computational capabilities and the availability of commercial finite element analysis software, there is a growing opportunity for further research in this domain.

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