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Fragility Models for Industrial Equipment Subjected to Natural Hazards

Oreste S. Bursi[a,*], Hafiz Liaqat Ali[a,d], Chiara Nardin[a], Marco Broccardo[a], Gianluca Quinci[b], Fabrizio Paolacci[b], Luca Caracoglia[c]

[a]University of Trento, Depart. Of Civil, Env. & Mechanical Engineering, Via Mesiano 77, Trento, Italy
[b]Roma Tre University, DICITA, Via Vito Volterra 62, Rome, Italy
[c]Northeastern, University, Depart. of Civil & Env. Eng., 400 Snell Eng. Center 360 Huntington Avenue, Boston, USA
[d]Department of Mechanical Engineering, Bahauddin Zakariya University, Multan 60000, Pakistan
Oreste.Bursi@unitn.it

Large cylindrical storage tanks are widely utilised in petrochemical plants to store different liquid materials, e.g., crude oil. However, these structures are revealed to be especially vulnerable in case of a natural event like an earthquake or tsunami. Damage to these tanks, indeed, can lead to technology accidents (also known as NaTech), like a spill of dangerous materials or waste of filling, typically through failed sealings.
To address the challenges of leakage modelling, fragility models associated to leakage due to seismic loading conditions of large cylindrical storage tanks, specifically a broad tank endowed with a single-deck floating roof, are studied. In particular, this paper aims to utilise a probabilistic model to evaluate fragility curves associated with leakage due to slosh-induced damage of single-deck floating roofs and/or seals of broad tanks. The assessment of failure mechanisms and leakage of pantograph-type mechanical seals is considered by means of local FE models. In addition, refined FE models of broad tanks with floating roofs are considered too. Specifically, a broad tank TK-59 endowed with an 86 m diameter and a 22 m height storing crude oil was selected and investigated as an industrial case study. Finally, fragility functions are derived and commented upon for the most relevant limit states associated with leakage.

1. Introduction

Storage facilities play a significant role in supporting the numerous petrochemical and processing activities of modern production industries, ensuring their uninterrupted operation. However, these facilities are at risk of accidents that fall under the category of Natural Hazards Triggering Technological Accidents (NaTech). The release of hazardous materials or the depletion of essential resources from such accidents triggered by external natural events such as earthquakes is demonstrated by Salimbeni et al. (2023) and Ge et al. (2024). In the last decades, natural catastrophes like tsunamis and earthquakes caused extensive damage to storage reservoirs of oil, petroleum and chemicals primarily resulting in major economic loss (Alfanda et al., 2022). Fragility models particularly seismic fragility functions are quite effective for determining structural vulnerability. These models support risk management strategies by accurately estimating seismic risk (Bezir et al., 2022). Their key aspects include seismic fragility curves and leakage risk assessment. Typically, vulnerability data is displayed using fragility curves. These curves are the graphical description of seismic fragility displayed as a function of intensities (López and Mayoral, 2020).
In this regard, Mayorga et al. (2019) developed a Monte Carlo simulation (MCS) based fragility model for storage tanks. Caprinozzi et al. (2020) conducted a dynamic study in which the seismic risk of liquid overflowing in a single-deck floating roof steel tank was examined. The simplified model was compared with a refined FE model for seismic fragility analysis. It seemed that fragility curves were highly influenced by liquid filling in storage tanks. Besides, floating roof tank seismic performance was both numerically and experimentally assessed by Caprinozzi et al. (2021), highlighting the risks posed by significant vertical alterations during major earthquakes, which might result in roof failure and content loss. The assessment of risk was conducted using a refined FE

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framework, subsequent simplified models (SM) and shaking table test experimental results. The FE model exhibited the highest accuracy prediction for floating roof displacement with respect to the SM. Cacciatore et al. (2010) performed a contact pressure analysis (CPA) for floating roof tanks subject to earthquake response using the Abaqus software, which caused sloshing waves on the roof. The floating roof deformation and stress distribution were estimated under seismic loads. They applied a novel CPA approach under seismic loadings. Additionally, the seismic liquid sloshing response for the floating roof tanks was estimated using both convective and impulsive mass. Furthermore, the seal performance under seismic loading in a full-scale double-deck floating roof tank was also assessed by Doustvandi et al. (2023). Quasi-static and vertical free-vibration tests were performed on the seal to evaluate its mechanical properties and the horizontal movement of the floating roof. Wang et al. (2023) demonstrated the efficacy of a different fragility model in assessing the seismic vulnerability of floating roof storage tanks. Tank bottom uplift had the highest likelihood of happening, according to an analysis of four fragility curves. Design circumstances should be given more consideration to reduce seismic fragility.

1.1 Scope

This study focuses on the development of fragility models for single-deck floating roof broad storage tanks subjected to earthquakes. It assesses the probabilistic model to handle the leakage and damage in case of sloshing. Seismic events cause the vibration of floating roofs which results in sloshing waves. This exerts vertical and horizontal stress on the seal causing it to break and resulting in leakage. The fragility curves provide a clear indication of the probability distribution over various damage states that are useful in decision-making for hazard assessment and possible mitigation approaches in the gas and oil industry as reported by Alessandri et al. (2017). This paper is divided into five sections. Section 2 provides an outline of the basic operation, characterization, and seismic damage states of floating-roof single-deck broad tanks along sealing mechanisms. Section 3 deals with the refined FE model for dynamic analysis of floating roof broad tanks through Abaqus/Explicit software, while Section 4 summarizes the industrial case study for key components of the broad tank (TK-59) floating roof and seals damage scenarios under seismic risk analysis. Lastly, Section 5 highlights the significant outcomes and future directions of the research work.

2. Industrial case study of a broad tank with a single-deck floating roof

2.1 Storage tank basic operation and characterization

Floating roof tanks can be categorized into two main types, i.e., internal and external floating roof tanks. External floating roofs are classified into double-deck and single-deck floating roof tanks as reported by Kuan (2009) and Noaman et al. (2016). Floating roof tanks, as indicated by name have a roof that floats above the top layer of the liquid material (such as crude oil or gas) stored in the tank. Figure 1 shows a floating roof tank whose dimensions are indicated in Table 1 with the floating roof placed at the base. The major advantage of these tanks is that they reduce evaporation loss and adhere to environmental emission standards. This accounts for floating roof tanks considered the best and most eco-friendly solution for the storage of flammable materials. This mechanism also reduces the risk of boilover or sudden boiling. In this study, the floating roof diameter determines a total gap of 400 mm with respect to tank walls. The gap between the inner wall of the broad tank and the outer edge of the roof is protected using a flexible sealing mechanism, i.e. a mechanical pantographic type of shoe seal, which helps to maintain the correct position of the roof and makes its movement smooth. The single pontoon types of floating roofs were analysed in this study.

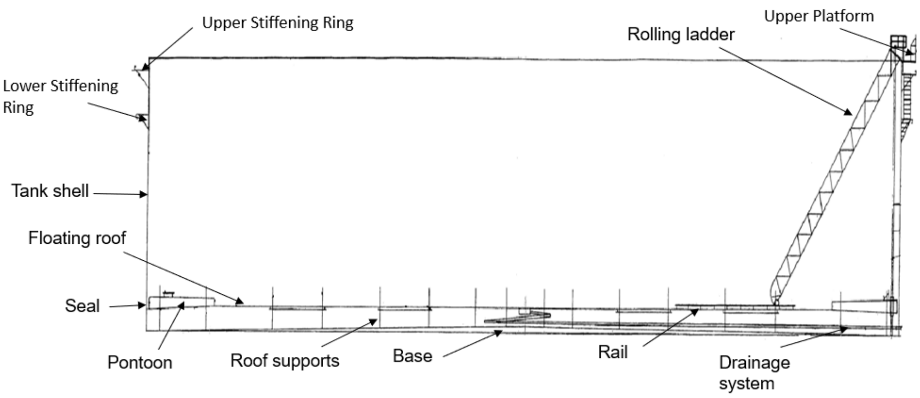


Figure 1: Case study: single deck floating roof broad storage tank (TK-59).

The single pontoon roof is the most common, the buoyancy of which depends on an outer circular pontoon that is divided into sections. The middle part of this roof consists of a membrane of steel plates, welded to the inner edge of the pontoon, and this structure helps the roof to float on the liquid surface. The floating roof broad tank material properties, i.e., Poisson's ratio, modulus of elasticity, and density, were 0.3, $2.1x10^{11}$ N/m², and 7850 kg/m³, respectively. The main characteristics of the single-deck, floating-roof broad tank (TK-59) are shown in Table 1.

Table 1: Characteristics of TK-59.

Parameter	*Units*	*Value*
Material	*[-]*	*Steel*
Diameter	*m*	*86*
Stored fluid	*[-]*	*Crude oil*
Height	*m*	*22*
Stored capacity	*m^3*	*125721*

2.2 Typical seismic damages to broad storage tanks

Roof deflection and sealing failure are major problems in large storage tanks during an earthquake. Shaking of the liquid in the tank with seismic forces causes high pressure on the roof, especially in floating roof designs. These stresses mainly due to sloshing, can cause the roof and shell to bend or lose its shape and buckle, as exposed in Figures 2(a) and 2(b). Roof deflection can increase the risk of sealing failure, allowing stored liquid to escape or external contaminants to enter the tank. Sealing failure is particularly serious in tanks storing hazardous materials, as it has the potential to contaminate the environment and create major safety hazards (see Figure 2c). Therefore, it is extremely important to ensure a strong roof design and effective sealing system to prevent earthquake damage and avoid leaks or spills, as reported by Malhotra (2006), and the latest research by Zdravkov and Pantusheva (2019), Luo et al. (2022), and Doustvandi et al. (2023).

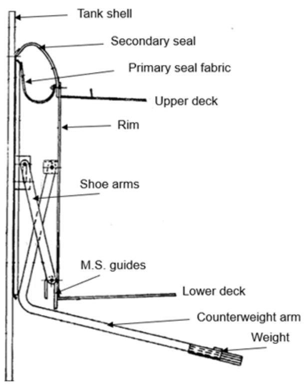
(a) Roof and roof-shell (b) Product spillage (c) Seal from above of the roof

Figure 2: Broad storage tank damages due to sloshing waves.

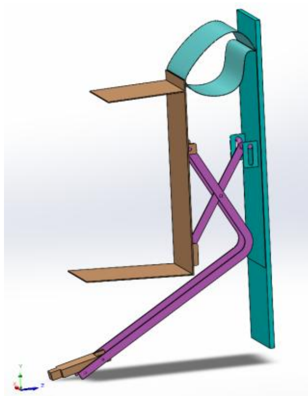
2.3 Single deck floating roof seal system

The sealing system for the floating roof broad tank is usually classified into two groups: the primary seal and the secondary seal. In the current study, the primary pantograph-type mechanical shoe seal was adopted, as indicated in Figure 3. The primary seal core function is to avoid the release of vapour from the broad tank; it acts as the first protective barrier. This seal covers the gap between the tank wall and the floating roof, which changes with the movement of the roof. Pantograph seal is also well-suited for environments where chemically reactive or aggressive products are stored, offering enhanced protection in challenging conditions.

Figure 3 (a) shows the pantograph seal with main details whereas Figure 3(b) represents the SolidWorks model of the pantograph. In particular, the pantograph seal uses a weight to increase upward pressure from the liquid; however, unlike conventional weighing systems, the pantograph designs utilize lighter and thinner materials such as carbon steel and aluminium, eliminating the need for heavy weights. By generating pressure with the help of liquid, this system provides consistent and reliable sealing performance without the need for added weight. Nonetheless, the pantograph-type seal can suffer severe damage with a seal failure and consequent leakage, when sloshing due to seismic loading entails vertical and horizontal movements of the floating roof.



(a) *Pantograph-type seal*



(b) *SolidWorks model of a pantograph-type seal*

Figure 3: Details and models of a pantograph-type mechanical shoe seal.

3. Refined FE model of a case study

In this study, the seismic behaviour of a floating roof broad tank with a single deck was analysed using a refined FE model created in Abaqus/Explicit software as shown in Figure 4. The model consisted of four core components, which were integrated into the software assembly function. First, an analytical rigid surface was created, as presented in Figure 4. The Abaqus software supports both three-dimensional (3D) and two-dimensional (2D) solid surfaces; however, a 2D analytical surface was chosen to simplify the contact with the tank, as it occurs in a single plane. Also, analytical rigid surfaces are less computationally challenging compared to discrete surfaces and do not affect weight or stability properties.

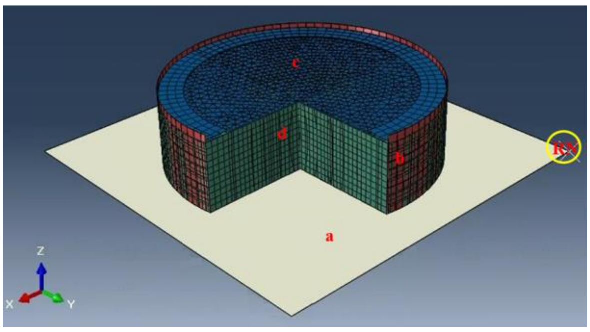


Figure 4: The broad tank refined FE model.

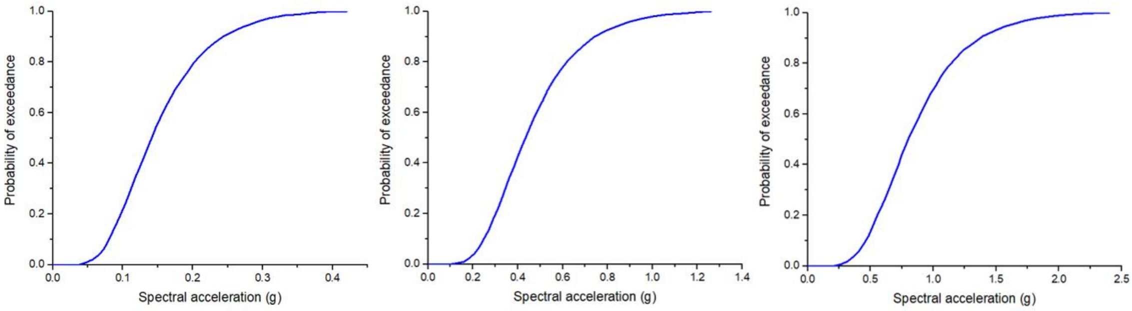
Table 2: Properties of liquid content.

Parameter	*Units*	*Value*
μ	$N/m\ s$	1×10^{-3}
ρ_l	kg/m^3	998.2
C_0	m/s	1482
Γ_0	[-]	0
s	[-]	0

The second part of the broad tank model includes the wall and floor, which are represented using S4 shell elements with complete numerical integration. This element was selected because it does not require hourglass controls and effectively avoids issues related to transverse shear locking. To enhance computational efficiency, it was assumed that the material of the steel broad tank behaves as a linear elastic body. The third part consists of the floating roof (Figure 4), which was also modelled using S4 shell elements, similar to the tank. The roof comprises two components: an inner plate and a circular outer ring, which were modelled separately and then welded together. The floating roof was constructed using stainless steel Fe 52 D ($f_{yd} = 355\ MPa$), treated as a linear elastic material during the simulation. The final part of the model represents liquid, which was modelled in Abaqus using the adaptive meshing technique and the arbitrary Lagrangian-Eulerian investigation. The liquid properties are revealed in Table 2. Where μ is the dynamic viscosity, ρ_l is the liquid density, s is the slope of the Us-Up curve, Γ_0 is the Grüneisen ratio, and C_0 is the velocity of sound in the medium. This approach was essential to accomplish the large deformations caused by the sloshing of liquid during an earthquake. Default parameters for mesh refinement and frequency were employed to ensure mesh quality. Liquid content is represented by the C3D8R solid element, a simple 8-node brick element (see Figure 4), and its behaviour was governed by the hydrodynamic material model, incorporating a linear equation of state, as reported by Caprinozzi et al. (2021). In this study, particular focus was given to modelling the contact between different parts. Two types of contacts were used in the modelling of a broad tank: a frictional contact among the rigid surface and bottom plate, and a frictionless contact among the liquid content, floating roof, and tank wall. These contacts were modelled as 'hard contact' to prevent the parts from merging while allowing for separation, which is necessary during the lifting of the tank in an earthquake. The refined FE model not only facilitated a detailed analysis of the earthquake behaviour of the roof but also enhanced computational efficiency by employing appropriate modelling techniques for each part of the system.

4. Fragility assessment of the case study

Fragility curves play a fundamental role in seismic hazard assessment, providing a probabilistic tool for structural performance during earthquakes of varying magnitudes. In this respect, Kameshwar (2017) used logistic regression methods for non-brittle failures and brittle failures for fragility assessment under seismic loadings. Two-layer metamodels were used: the structural response used the first layer, and logistic regression used the second layer for leakage probability and fragility assessment. Brittle failures used binary classifiers for sudden outcomes, while non-brittle failures used metamodels for continuous responses. Non-linear time-history analyses and FE modelling are often used for this purpose to better comprehend the connection among the fluid and the structure. Failure probabilities were predicted through probabilistic techniques such as MCS or logistic regression, which help in improving design and reducing seismic hazards, as explored in the work of Phan et al. (2020) and Caprinozzi et al. (2020). In particular, the fragility function $P[D \geq C|IM]$ is defined as the probability of the exceedance of the demand D over the limit state capacity $C,$ given an intensity measure (IM). The fragility function can be estimated through MCS, which is well-defined as a proportion of the number of points in order that $D \geq C$ and the overall points.



(a) *(b)* *(c)*

Figure 5: Typical fragility curves for Tank 59: (a) *90% of the filling level; (b) 80% of the filling level; and (c) 70% of the filling level.*

The outcomes of overtopping probabilities for steel storage broad tanks with single-deck floating roofs under different earthquake levels with liquid contents filled up to 90%, 80%, and 70% for the spectral acceleration at the period of 4 s are shown in Figure 5. Through the reduced filling level of liquid content, the broad tank has more freeboard (space above the liquid), resulting in a lower probability of overtopping at the same spectral acceleration level. The 90% fill level curve, see Figure 5(a), represents the greatest risk, as the exceedance probabilities increase at lower spectral accelerations than for curves for lower fill levels, due to reduced freeboard. This risk is reduced with low liquid levels. On the other hand, the curves referring to 80%, see Figure 5(b), and 70%, as shown in Figure 5(c), are pushed to the right, indicating that much higher seismic intensities are necessary to achieve the same probability of overtopping, showing a significant reduction in seismic risk.

5. Conclusions and future developments

This study has examined the vulnerability of structural components under seismic loading, with particular attention to the fragility of leakage due to buckling of single-deck floating-roof or /and seals of broad storage tanks. The relevant refined FE model established was effective in successfully modelling the broad tank response subjected to earthquakes. In particular, the aforementioned model accurately captured the interaction between fluid and single-deck floating roofs and contributed to the evaluation of potential failure mechanisms also associated with seals. Fragility functions of leakage were produced with standard techniques, and the results indicated that floating roofs and seals are vulnerable to damage and can entail significant leakage. This result also supports the claim that the level of liquid content significantly affects tank vulnerability during an earthquake. The higher the liquid level, the greater the risk of structural damage and leakage. The exceedance probability was predicted to be highest at spectral accelerations of 0.42 g and 2.4 g for filling liquid levels of 90% and 70%, respectively. This research can be further expanded in the future, where the accuracy of fragility analyses for leakage estimation due to failure sealings and floating roof buckling will be improved. Finally, both refined and simplified FE models of broad tanks could be improved to increase the accuracy of the proposed results.

Nomenclature

CPA – contact pressure approach
FE – finite element
IM – intensity measure
MCS – Monte Carlo simulation
NaTech– natural hazard triggering technological disasters
PGA – peak ground acceleration
SM – simplified model

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