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Fragility Analysis of Atmospheric Storage Tanks by Observational and Analytical Data

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Abstract
In this research, seismic fragility analysis of storage tanks is carried out with a large damage database from past earthquakes and analytical studies. At the fragility analysis, a new damage state has been defined. Peak ground acceleration is employed as an intensity measure. Epistemic and aleatory uncertainties are considered. At the observational fragility analysis, logit, probit and cumulative lognormal model and maximum likelihood method are utilized. In this research, Finite Element Analysis is also performed. As a result, new seismic fragility curves for storage tanks obtained and compared with the existing tank fragility curves in the literature.

Keywords Atmospheric storage tanks · Fragility curves · Finite element analysis · Structural reliability · Uncertainty · Seismic analysis

1 Introduction

Storage tanks are structural elements that are classified based on their positions compared to ground level (e.g., above, or belowground). In this study, all analyses and calculations will be realized for above ground storage tanks. These structures are utilized to store any conceivable liquid like water (for firefighting and drinkable water), petroleum and oil derivatives, liquefied natural gas, and other chemical fluids. Industrial tank facilities are of great importance in many ways. For a possible earthquake, human life, environment, and economy would be under great hazard due to potential incidents (e.g., fire, explosion, and toxic chemical substance spillage). In possible earthquakes, uncontrollable fires, toxic chemical spills may occur in tank facilities; as a result, the global economy and the environment may be damaged, and large number of people may be injured or killed. For these reasons, the importance of storage tank safety is clear. The Kocaeli Earthquake in 1999 can be given as a recent example. Secondary events such as fire and explosion caused by the primary events can come into being because of the domino effect may result in more severe accidents than the primary effect and originate great damage in tanks, the environment, and perhaps in the entire facility (Cozzani et al., 2005). In Kocaeli Earthquake, 115 m height chimney of Plant-5 in TUPRAS refinery has collapsed. After the primary effect, fires broke out in the tanks which spread to the refinery. On the second day of the fire, the number of tanks in fire has increased to eight (Sari and Korkmaz, 2007). The refinery was the seventh biggest petrochemical refinery in Europe, and also had 220,000 barrels of oil processing capacity daily (Johnson, 2002). According to the preliminary damage assessment studies, the amount of imprecise damage was to be 115 million dollars with an error margin of 15 percent (Ozbey and Sari, 2007). Thus, the economic dimension of the accident caused by the domino effect can be visualized in this way. Since the tank facilities are close to the coastal

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areas, the soil in these areas is soft and prone to serious seismic hazard. These areas are seismically more sensitive, and this fact has been proven by damages from the past earthquakes. Often tank facilities are generally located close to coastal areas where serious earthquakes can occur, and soil amplification can take place. Therefore, these regions are more sensitive in terms of seismicity. This fact has been observed in past earthquakes often, such as Emilia (Italy) in 2012, Tohoku (Japan) in 2011, Chile in 2010, Kocaeli (Turkey) in 1999, Kobe (Japan) in 1995, Niigata (Japan) and Alaska (USA) in 1964. They caused significant damages to industrial facilities (Berahman and Behnamfar, 2007; Korkmaz et al., 2011; Myers, 1997; Razzaghi and Eshghi, 2015).

The past seismic events demonstrate that there are several forms of earthquake-based tank damages. It is not simple to estimate the tank dynamics owing to the complex dynamic behaviors under the earthquake excitation. There are parameters which are effective in damages, such as slenderness ratio, anchorage status, roof type, filling level. The slenderness ratio is one of the main parameters which trigger tank damages. As the slenderness ratio of the tank increases, the tank becomes more prone to acting as a cantilever. This leads to high stresses and a serious amount of overturning moment at the base. Because of this, elephant foot buckling (EFB) and uplifting, junction damages such as rupture between the base shell and bottom parts, buckling of the bottom shell, deterioration of the piping system (inlet/outlet), anchor failure, shell buckling in the middle part of the tank shell are damages likely to occur in this case. Roof and upper shell damages are not common in slender tanks. For this reason, damage to the tank roof and upper shells can be excluded from this category. At the broad tanks, because of the sloshing effect of the contained fluid, damages mostly take place at the upper part of the tank. The buckling at the top of the shell and at roof, failure between the tank wall and roof shell connections and failure of roof sustaining columns and rafters are common damage forms at the squat tanks due to the sloshing of fluid. Since the tank height is relatively higher in slender tanks, the overturning moment at the bottom of the tank is more effective. Therefore, anchors that connect the tank to the ground are of great importance in this type of tanks. When the tanks are subjected to the strong ground motion; anchor pulling out, stretching and anchor failure are possible damages that may take place. Loss of the content is not common at this damage mechanism. When it comes to the damage that is related to the roof**,** sloshing motion becomes important. If the filling level is close to the tank height, the convective mass motion represents the mass of the upper part of the liquid. This leads to the tank-fluid system oscillating in a long period. This oscillation is efficacious on the upper parts of the tank wall and creates high liquid waves (Cooper, 1997). In the case of a fixed roof tank**,** which is almost full, sloshing motion causes pressure onto the roof. Extensive damage at the roof or upper course of the shell wall may result in loss of tank content, yet this loss is minimal compared to the loss of content at the lower parts when content releases in case of damages like pipe-tank wall connection failure or tank shell rupturing.

Tank shell buckling may appear in different ways that are elastic, elastic–plastic and bulge formation. Elastic buckling is named as diamond buckling because of the configuration of deformation and related to the elastic property of the shell material. Diamond buckling happens above the lower part of the tank. Elastic–plastic buckling is known as elephant foot buckling (EFB) and appears at the lower part like a ring around the tank. The bulge formation is local bending deformations which are seen at the tank base owing to the restraints. Depending on these buckling formations, tears may be observed between adjacent walls or at the bottom-wall connections and inlet/outlet piping systems may be deformed or ruptured. Rupture at the piping system likely causes loss of tank content (D'Amico, 2018). Since the bearing capacity is low in soft soils, such soils may lose their strength during an earthquake and cause damage to the structure. For this reason, tank systems should be placed on compacted or high-strength soils. Thus, it will be less likely to see damage due to settlements and rotations on the bottom of the tank because of earthquakes. In 1964, after the Niigata Earthquake, the ground beneath the large crude oil tank settled several centimeters and caused the tank's connecting pipes to rupture and liquid leakage (Watanabe, 1966). As it is explained above, the most critical damage mechanism is one that can cause the release of the liquid by rupturing the tank shell or connections between tank and piping system. The releasing content may cause a fire or explosion and damage to other tanks or the entire facility due to the domino effect, and in some cases to be completely unusable. Some tank damage in recent earthquakes can be obtained from the Kocaeli earthquake reconnaissance report or from technical and academic research. (Sari, 2019; Sezen et al., 2000).

It has stated clearly that fragility analysis is an important step to perform loss estimation (O'Reilly et al., 2020). If the tank has been damaged after an earthquake, repair, retrofit or replacement of some part of the tank are likely necessary against next earthquakes or other threats. It is known that installation and use of storage tanks date back to the nineteenth century, and for more than 50 years, strict engineering guidelines and standards for the construction, material selection, design and safe requirements of storage tanks and their secondary equipment have been published by trade organizations and engineering societies such as American Petroleum Institute (API), American Institute of Chemical Engineers (AIChE), American Society of Mechanical Engineers (ASME), and National Fire Protection Association (NFPA) (Arthur & Levine, 1988; Center for Chemical

Process Safety, 2012; API, 2013; National Fire Protection Association, 1996). Seismic vulnerability information of old tanks that have not been extensively investigated and improved are required to continue facility operation and use these tanks. When earthquake induced past accidents in the storage tank facilities have been investigated, it is observed that these structures are under the threat of severe ground motions, their vulnerability closely depends whether storage tanks are designed in accordance with standards and codes or not. In 1999, an earthquake in Kocaeli, Turkey and in 2003, an earthquake in Bam, Iran proved this fact one more time (Ozbey and Sari, 2007). For engineers, decision-makers, or owners, it is essential to determine whether the facility should keep working. It is also important to determine retrofitting strategies when needed. In some cases, it may even be necessary to query codes and regulations and to improve their deficiencies if it is necessary. After such cases of the 1994 Northridge earthquake in the United States (Lindell and Perry, 1997) and 1999 Kocaeli earthquake in Turkey (Sezen and Whittaker, 2006; Scawthorn and Johnson, 2000), some revisions have been made in the codes and regulations. To clarify these statements, the seismic vulnerability of the system is the main requirement.

Seismic performance of cylindrical storage tanks entails definition of tank capacity against possible damage mechanisms as a function of seismic intensity measure such as PGA, $S_a(T)$, PGV or PGD. For such serious decisions, rather than a deterministic approach, probabilistic seismic safety evaluation (PSSE) needs to be taken into account. In this context, fragility curves are utilized to correlate earthquake intensity to the probability of reaching or exceeding certain limit states. In structural and earthquake engineering, estimation of seismic vulnerability is mainly based on two different approaches which are empirical and analytical. In the empirical approach, damage databases are gathered, and this issue often requires a difficult process since this data is mainly based on field observations after earthquakes. Considering the uncertain situation after earthquakes, it is seen that trying to collect the correct data requires serious efforts and, in some cases, it is restricted. When it comes to structures such as industrial facilities, storage tanks, it becomes difficult to gather information. Because earthquake damages occurring in different parts of the world are sometimes not completely shared, and even if they are shared, it is not easy to correctly identify the damage, since countries sometimes prefer to publish in their language. Furthermore, explosions and fires sometimes take place after earthquakes. Also, storage tanks can be damaged owing to the tsunami, and these bring about other difficulties to reach and detect earthquake induced damage data. The 1999 Kocaeli Earthquake and 2011 Tohoku Earthquake are good examples for this kind of cases (D'Amico, 2018; Fire & Disaster Management Agency, 2011; Hatayama, 2015). Even though this kind of information gathering is not easy, these studies are very important as the data and results belong to real damage records. For such important structures, there are many uncertainties from design to construction, and since the collected data reflect these facts, data collection issue is essential for targets such as performance evaluation of these structures and earthquake reliability. Analytical study based on finite element analysis (FEA) is another approach to performance evaluation. Modelling and analysis of storage tanks is a matter of effort and time, as it is important to reflect complex situations such as fluid–structure interaction and soil-structure interaction realistically. In addition, there are several kinds of storage tanks depending on their materials, design conditions, geometries. Therefore, this requires plenty of different mathematical models and a serious amount of computational effort. However, lack or empty data fields which are coming from field observations can be filled by using analytical study results. Furthermore, results are convenient and reliable if input model parameters are given carefully, and these parameters depend on existing tank geometries and design conditions. In this study, both statistical and analytical approaches are employed, even though there are all these difficulties. In the collected database, 4509 tank damage data were used from 31 different ground motions. This database was mainly composed by using storage tank damage data from several sources (O'Rourke and So, 2000; ALA, 2001; D'Amico and Buratti, 2018). Also, 101 storage tanks were modelled by using LS_DYNA 3D FEA software by considering uncertainties (LS-DYNA R11.0, 2017). Damage results of the numerical models were added to the database, and fragility analysis has been carried out as considering both empirical data only and including the results of finite element analysis.

The main motivation of this research is to obtain the fragility curves from the database which is created by finite element analysis and based on observational data. Since the most recent study in this area dates back to 2018, the authors decided to make an attempt to combine the existing real tank damage data with the large amount of numerical analysis ever since. Furthermore, most researchers have used certain statistical approaches to assess fragility analysis. O'Rourke and So have studied with 400 tanks in 2000 by utilizing logistic regression method (O'Rourke and So, 2000). In 2007, Berahman and Behnamfar investigated seismic fragility of 200 un-anchored storage tanks having 50% or greater filling level using Bayesian approach. In 2015, Razzaghi and Eshghi have considered the 750 pro-code tanks or other tanks that were designed based on early editions of seismic codes and they have depicted the result of FEA in their study as well. They used cumulative standard lognormal distribution in order to evaluate tank fragility (Berehman and Behnamfar, 2007; Razzaghi and Eshghi, 2015). Lastly, D'Amico and Buratti have examined 3026 tank damage data in 2018 using Bayesian approach. Although there is a great effort on storage tank fragility in the literature, a few researchers have focused on coping with the real damage data, and they have utilized several methods to evaluate tank fragility. Distribution of damage data is an important fact that needs to be considered in this kind of analysis. Depending on this distribution, one method can fit the data better than another one. In this study, maximum likelihood method, probit model, logit model and cumulative lognormal distribution model were used to observe which approach fits data in the best way. The details about statistical procedures are presented in Sect. 4.

2 Damage States for Fragility Analysis

Damage mechanisms for storage tanks originally defined and categorized by HAZUS (FEMA, 1999) in 1999, and most of researchers either have used this definition or have made some modifications on this. In 2000, O'Rourke and So have improved HAZUS's methodology including pipe damages (O'Rourke and So, 2000). In 2001, American Lifeline Alliance published an extensive report which has a broad chapter about storage tanks and used new damage definitions by adding new comments about repair costs and functionality impact (Eidinger et al., 2001). In 2003, Salzano et al. realized a framework for storage tank facilities in terms of risk assessment and used the damage definition of HAZUS (Salzano et al., 2003). In 2007, Behnamfar and Berahman adopted ALA's damage state in order to estimate storage tank failure probability (Berahman & Behnamfar, 2007). In 2015, Razzaghi and Eshghi also have benefited from HAZUS methodology, and D'Amico has utilized HAZUS's damage states by adding a few details to make the damage mechanism more certain and comparable in 2018. Also, in that research, damage was defined in the context of loss content (D'Amico, 2018; Razzaghi and Eshghi, 2015). In the research studied by D'Amico, for damage states, it has been taken into consideration tank structural performance, which is the most utilized and quite reliable method to estimate tank fragility from 1999 to now. Table 1 provides a detailed description of each damage state and the number of tanks classified accordingly. As can be seen from the definitions in Table 1, there is an increasing tendency in the damages from "no damage" to the "replacement" of the entire tank. In addition to this definition, additional explanations were made for the conditions such as liquid sloshing damage, pipe connection damage, and shell wall damage to the tank bottom, considering the leakage of the liquid stored in the tank under the effect of ground motion. All these damage definitions apply to steel atmospheric storage tanks where liquid substances such as petrol, water, wine, chemicals are stored.

3 Tank Damage Database

Past researchers have provided considerate data which depends on observations from past earthquake cases. In reliability of the fragility analysis, number of data is certainly an effective factor, this is more critical in case of the database which is dominated by empirical data because of errors in measurements, indirect nature of observation, uncertainties, and unknowns (D'Amico, 2018). This means quality is at least as important as quantity in fragility estimation. It is clearly stated in the introduction that data detecting was conducted meticulously in this study. Authors investigated all related sources and removed or improved some of them. In addition, in this study it is aimed to collect much more data compared to previous studies always taking into account the quality of data. Several different studies have been realized in this study field. In that studies (Berahman and Behnamfar, 2007; D'Amico, 2018; O'Rourke and So, 2000; Razzaghi and Eshghi, 2015; Salzano et al., 2003) it has been specifically studied on empirical fragility estimation of storage tanks. There has not any empirical study since then. The primary source was a report by NIST authored by Cooper. This study includes the damage data of storage tanks from 10 different earthquake cases (Cooper, 1997).

Table 1 Damage states definitions

Damage states	Damage description	Number of observational data	Number of numerical data
DS1	No damage or minor damage to wall, bottom, piping system, etc	4509	4610
DS2	Moderate damage to anchors, base shell, wall, piping, foundation, etc. Also, damage to roof and upper part of shell due to sloshing	1297	1398
DS3	Major damage to anchors, base shell, wall, roof, foundation, etc. Also, damage to piping system	724	728
DS4	Severe damage to anchors, base shell, wall, piping, roof, foundation, etc. Also, slight elephant foot buckling, damage to the shell-bottom plate junction	285	285
DS5	Part replacement, extensive EFB, damage to shell-bottom plate junction, shell or bottom plate, total failure, tank collapse, overturning	129	129

Later, ALA added 108 new damage data increasing these 424 tank damage data by Cooper and used 532 storage tank damage data for fragility analysis in 2001 (Eidinger et al., 2001). In 2018, D'Amico collected 3026 storage tank damage data from different sources (D'Amico, 2018). At that study, the author carried out a comprehensive data search. In the current study, the authors focused on fundamental sources which have performed up until to now to correct and improve those data.

As a result of gathering and checking all this information, 4509 tank damage data were taken into consideration in the database. The importance of this study field has been clearly discussed and proved in the introduction, and addition of new damage data is significant for such an important engineering issue. The summary of this database is clearly stated herein and provided at Table 2. In addition to all these observational data, 101 damage data were obtained from numerical analyses which are performed by using LS-DYNA 3D simulation software. All through these data, 4610 damage data were collected with cause of damages, PGA values, and characteristics of tanks. All these data belong to steel storage tanks. The tank sizes and material properties that were employed in the numerical analyses were obtained from existing storage tanks to increase the reliability of the fragility analysis.

Table 2 Tank database

Earthquake, year	PGA ranges (g)	Tank number	References
Long Beach, 1933	0.358–0.448	52	Cooper, (1997)
Kern County, 1952	0.114–0.351	64	Steinbrugge and Moran, (1954)
Alaska, 1964	0.20–0.384	40	Hanson, (1973); Belanger, (1973)
San Fernando, 1971	0.12–0.86	35	Cooper, (1997)
Managua, 1972	0.39	3	Eidinger et al., (2001)
Miyagi, 1978	0.285	73	Kawano et al., (1978)
Imperial Valley, 1979	0.378–0.467	29	Brandow and Leeds, (1980); Haroun, (1983)
Greenville, 1980	0.167	1	Stratta, (1980)
Coalinga, 1983	0.187–0.45	52	Scholl and Stratta, (1984); Kiremdijan et al., (1985); Mavko et al., (1985)
Central Japan Sea, 1983	0.05	3	Fire Department Dangerous Goods Security Room, (2011)
Chile, 1985	0.23–0.28	163	Pineda et al., (2012); EERI (1986); Connor, (1985); Booth and Taylor, (1988)
Adak, 1986	0.2	3	Eidinger et al., (2001)
New Zealand, 1987	0.30–0.50	11	Hashimoto and Tiong, (1989)
Loma Prieta, 1989	0.10–0.55	1824	Cooper, (1997); EERI and National Resarch Council, 1989; EEFIT, (1993); Schiff and Holzer, (1998); Ballantyne and Crouse, (1997)
Costa Rica, 1991	0.24	37	Mitchell and Tinawi, (1992); Shea, (1991); Santana, (1992)
Landers, 1992	0.19–0.553	33	Cooper, (1997); EQE and Engineering and Consulting, (1993)
Northridge, 1994	0.23–0.90	104	Merriman and Williams, (1994); Cooper and Wachholz, (1994); Hall et al., (1995)
Chi-Chi, 1999	0.057–0.137	6	Yochida et al., (2000); Zama, (2003)
Kocaeli, 1999	0.23	50	Sarı and Korkmaz, (2007); Sezen and Whittaker, (2006); Girgin, (2011); Sezen et al., (2000); Suzuki, (2002); Steinberg et al., (2001)
Bhuj, 2001	0.236	2	EERI, (2001); Madabhushi and Haigh, (2005)
Bam, 2003	0.413–0.497	7	Eshghi and Razzaghi, (2005); Eshghi and Razzaghi, (2004)
Tokachi-Oki, 2003	0.1	177	Hatayama, (2008)
Zarand, 2005	0.205	11	Razzaghi and Esghi, (2015)
Silakhor, 2006	0.12–0.44	28	Razzaghi and Esghi, (2015)
Central Peru, 2007	0.34–0.474	104	Taucer et al., (2009); Hopkins et al., (2008)
Haiti, 2010	0.78	2	Edwards, (2012)
Chile, 2010	0.24–0.334	202	Pineda et al., (2012); Herrera and Beltran, (2012); Moehle et al., (2010)
Tohoku, 2011	0.031–0.359	33	Fire Department Fire Research Center, (2011) (in Japanese)
New Zealand, 2013	0.11–0.40	546	Yazdanian et al., (2020); Davey, (2010)
Napa Valley, 2014	0.234–0.65	12	Fischer, (2014a, 2014b); Almutfi et al., (2014)
New Zealand, 2016	0.23–0.36	802	Yazdanian et al., (2020); Davey, (2010)

4 Statistical Approaches

In this section, technical information about the fragility analysis of atmospheric steel storage tanks is given. Fragility curves are an important tool that shows the relationship between the ground motion intensity measure and damage to structures. Fragility curves are defined as the probability of reaching or exceeding a certain damage state as a function of the ground motion parameter (herein PGA) under earthquake excitation. Fragility curves can generally be generated in three different ways. The first of these is empirical (observational) fragility curves. This method is based on the damage data collected as a result of field observations after the earthquakes. The observed data can be in the form of a binary variable depending on the damage states (probability of reaching or exceeding a specific damage state is assigned as 1, otherwise 0). In addition, another method of generating empirical curves is to use damage matrices. For this, the ground motion intensity measure is divided into uniform ranges based on the information contained in the dataset and the number of tanks corresponding to each range is determined for any damage states. The probability of observation, which indicates the relationship between ground motion intensity and probability of damage, is calculated by dividing the number of tanks in this range by the number of all tanks belonging to the damage state in question. Then, with the curve fitting process to these data, fragility curves are obtained. There are also different statistical methods to fit the curve. The second method used to obtain the fragility curves is the analytical method. Analytical fragility curves depend on structural modelling and analysis of simulated tank behavior. Modelling conditions and assumptions must be realistic to overcome the shortcomings in the literature. Another method for obtaining fragility curves is based on expert opinion. In this method, fragility analyses are made based on the predictions and interpretations made by the experts on the subject. The statistical procedures considered in the obtaining the fragility curves in this research are logit and probit models, cumulative lognormal distribution, maximum likelihood method. Brief information about these methods is presented below.

4.1 Logit Model

When the dependent variable (Y_i) investigated in using statistical methods presents a normal distribution, analyses can be made by linear means. However, the dependent variable is not always continuous and does not present normal distribution. In cases where the dependent variable does not present a normal distribution, it is inadequate to apply with linear models since many assumptions are not fulfilled when there is a binary or higher level (polychotomous), classified (nominal) or ordered (ordinal) qualitative variable. The linear structure cannot be established between the average of the dependent variable and one or more independent variables. In this case, Generalized Linear Models (GLMs), a wider state of linear models, are used in the analysis (Agresti, 2002).

To ensure that the values that the dependent variable (Y_i) can take is between 0 and 1, one of the models that gives the relationship between the independent and dependent variable curvilinearly is the logit model. In this model, the following logistic distribution function is used.

$$\pi\left(x_i\right) = E(Y_i = 1|x_i) = \frac{e^{\beta_0+\beta_1 x}}{1 + e^{\beta_0+\beta_1 x}} \tag{1}$$

$\boldsymbol{\beta}_0$ and $\boldsymbol{\beta}_1$ in Eq. (1) are the logistic regression parameters. $\boldsymbol{x}$ values present the intensity measures (herein PGA).

4.2 Probit Model

This model is used when the dependent variable is a binary variable. The cumulative normal distribution function of this model is given as (Gujarati, 1988):

$$\pi(x) = \Phi\left(\frac{\ln(x_i) - \mu}{\sigma}\right) = \Phi\left(\alpha + \beta.\ln\left(x_i\right)\right) \tag{2}$$

Here, Φ represents the standard normal cumulative distribution function, and α and β represent unknown regression parameters fitted from the probit model. Regression parameters α and β are related to the median value of $ln\left(x_i\right)$ and dispersion parameter, respectively.

$$\mu = -\alpha.\beta^{-1} \tag{3a}$$

$$\sigma = 1/\beta \tag{3b}$$

Probit model is a linear method in terms of the model parameters and a nonlinear statistical method in terms of probability. The main difference between the probit model and the logit model is the distribution functions used. While logistic cumulative distribution function is used in the logit model, the normal cumulative distribution function is used in the probit model. The reason for this is that in the probit model, the basic dependent variable is assumed to be normally distributed, while in the logit model this variable is distributed in the form of a logistic curve (Aldrich and Nelson, 1984).

4.3 Cumulative Lognormal Distribution

In this method, a lognormal cumulative distribution function is employed in creating the curve. The probability of failure is defined as follows:

$$\pi\left(x_i\right) = \Phi\left(\frac{\ln(\mathrm{IM}_i) - \mu_j}{\sigma_j}\right) \tag{4}$$

Here, the mean and standard deviation values are obtained depending on the logit model parameters. It is seen that if these values are taken from the standard lognormal cumulative distribution function or probit function, the curves give more distant results than the curves fitted by other methods.

4.4 Maximum Likelihood Method

In models with binary response variables, one of the methods used to estimate the parameters of the data set is the maximum likelihood method. In the method, parameters are estimated to, maximize the probability of the observed values as much as possible. A likelihood function must be created to implement this method. This function expresses the probability of observed data as a function of unknown parameters. $\pi(x)$ is the conditional probability that provides $Y = 1$ for a given x value and is denoted as $P(Y = 1|x)$ and $1 - \pi(x)$ is the conditional probability that provides $Y = 0$ for a given x value and is expressed as $P(Y = 0|x)$. Thus, the contribution of $\left(x_i, y_i\right)$ pairs to probability function is expressed as:

$$l\left(\beta_0, \beta_1\right) = \prod_{i=1}^{n} \pi(x_i)^{y_i}\left[1 - \pi(x_i)\right]^{1-y_i} \tag{5}$$

With the maximum likelihood method, it is aimed to find β_0, β_1 values that increase the equilibrium in Eq. (5) to its maximum value. When the natural logarithm of this expression is taken separately by the parameters β_0 and β_1, the results are given in Eq. (6) and Eq. (7) (Baker, 2015; Ozturk et al., 2019).

$$\sum\left[y_i - \pi(x_i)\right] = 0 \tag{6}$$

$$\sum x_i\left[y_i - \pi(x_i)\right] = 0 \tag{7}$$

These equations are nonlinear equations according to the parameters β_0 and β_1. Iterated methods are required for the solution. Statistical software like SAS and JMP or mathematical software like MATLAB can be used for the solution (SAS Institute, 2013; JMP Version 15, 2019; MATLAB Release, 2016b). In this study, unknown parameters were calculated with the SAS program. Here, in the fragility formulation, fitting can be performed using the lognormal cumulative distribution function or other different functions. In the study, the logistic regression function was taken into consideration and unknown parameters were calculated with maximum likelihood method.

5 Finite Element Modelling and Analysis Procedures

Evaluation of fluid–structure interactions can be investigated analytically, experimentally, and numerically. The derivation of an analytical solution for the sloshing response of a liquid in a tank includes various assumptions and simplifications on the tank material, fluid properties, initial and boundary conditions. Even though experimental works are necessary to study the actual behavior of the system, they are time consuming and very costly. However, an appropriate numerical method with fluid–structure interaction techniques can efficiently predict the response of the tank (Özdemir, 2012).

Fluid–structure interaction (FSI) algorithms of the finite element method (FEM) are employed to evaluate the seismic response of a tank by LS-DYNA (LS-DYNA R11.0, 2017) in the present study. The effects of geometric and material nonlinearities of the tank, buckling of the tank shell and nonlinear sloshing behavior of liquid are taken into account to evaluate the behavior of tanks. The Arbitrary Lagrangian–Eulerian (ALE) formulation over Lagrangian methods, interaction effects between fluid and structure are modelled by utilizing the ALE method which permits formation of large structural and fluid deformations. Real tank models with different proportions and material properties are analyzed under different earthquake records by employing an explicit time integration scheme based on central difference method. Analysis results obtained for different ground motion records and loading combinations are evaluated in terms of sloshing, shell stresses, and plastic strain. Also, the damage level is to be determined for all analysis results. Figure 1(a, b, c) demonstrates tank models that have different roof types respectively.

6 Evaluations of Fragility Curves

In the study, fragility analyses of atmospheric liquid storage tanks are carried out. Fragility curves were generated using 4509 tank damage data from 31 different earthquake events in the past and 101 tank damage data from the finite element analysis. Table 3 shows the regression parameters calculated with the maximum likelihood method for the data for each damage state. Fig. 2a shows how finite element analysis affects curves for each damage state. Figure 2b illustrates comparison between fragility curves in this study

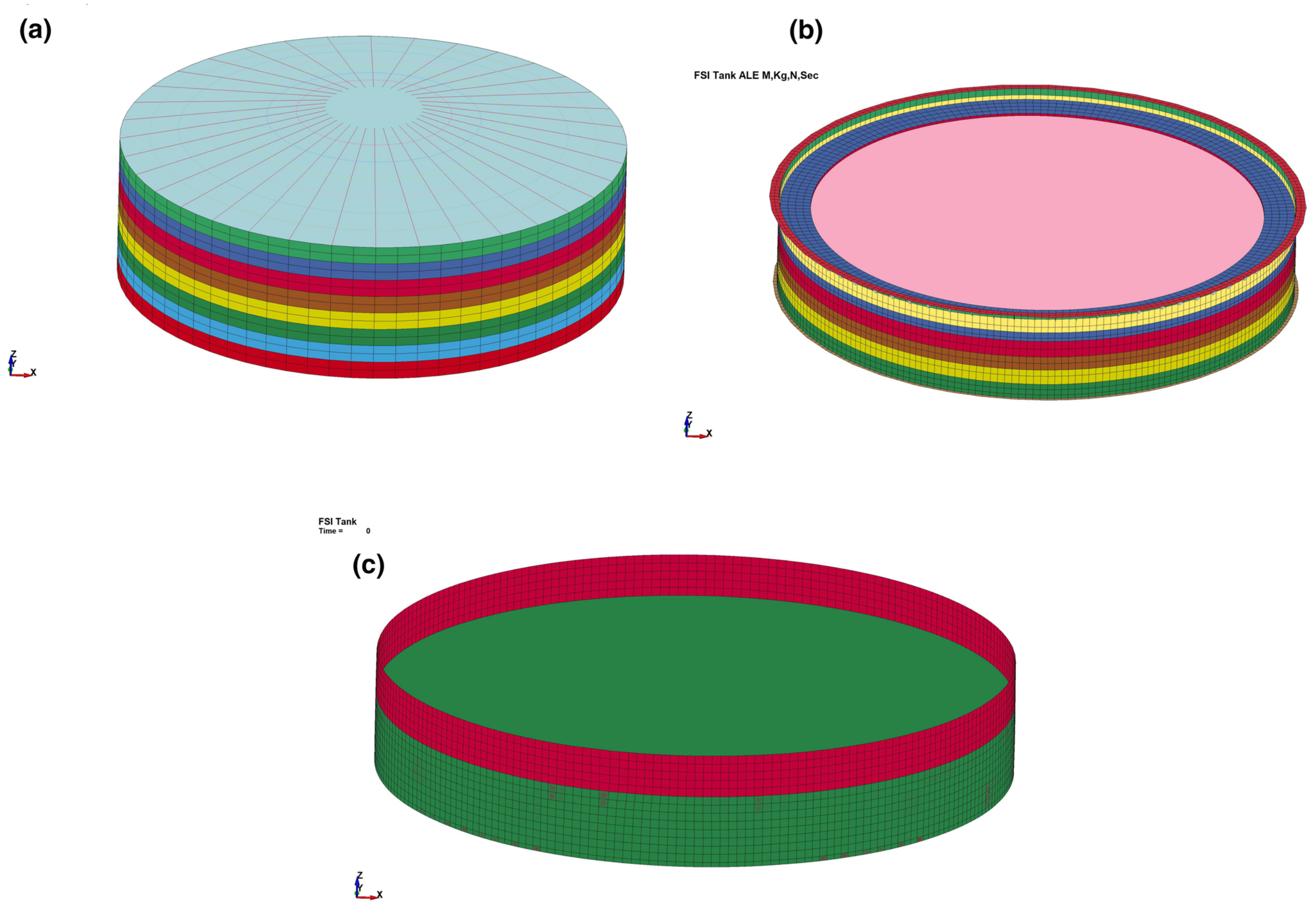

Fig. 1 Storage tank with **a** fixed roof, **b** floating roof, **c** open roof

Table 3 Regression parameters obtained by MLE

Damage State	Including FE analysis		Excluding FE analysis	
	β_0	β_1	β_0	β_1
DS2	2.629	− 7.842	2.552	− 7.360
DS3	3.178	− 6.128	3.528	− 7.746
DS4	4.640	− 7.083	5.111	− 8.975

and HAZUS curves. In Fig. 3a–d fragility curves obtained by different methods for each damage state are shown. In Fig. 4a–d) the effect of the finite element analysis is shown on the data representing the probability of observing each damage state.

Figure 5 shows the fragility curves of the fixed roof tanks. Since the number of the fixed roof tanks is higher than the others in the database obtained, the curves of these tanks were generated. However, analytical studies will be increased to examine the effect of different roof types in future studies. In addition, the HAZUS fragility curves in the literature have been generated in different categories as "anchored" and "unanchored". Since only the anchorage status of the tanks in the database obtained in the study, it is not clear whether the HAZUS curves are used for unanchored tanks. That is why some differences have occurred.

7 Conclusions

It is known that domino effects that may take place after the earthquakes in the industrial facilities can cause huge damage to the facilities and the environment. In this respect, new and comprehensive fragility curves were derived for atmospheric storage tanks in this research. A large database containing tank damage data which is available in the literature have been further expanded with the new findings. 4509 tank damage data were obtained and used from different earthquake events and observational (empirical) fragility curves were obtained by taking this information into consideration. In addition, 101 tank damage information obtained from finite element analysis also included in the database. Thus, the effects of the numerical studies on the fragility curves were also examined.

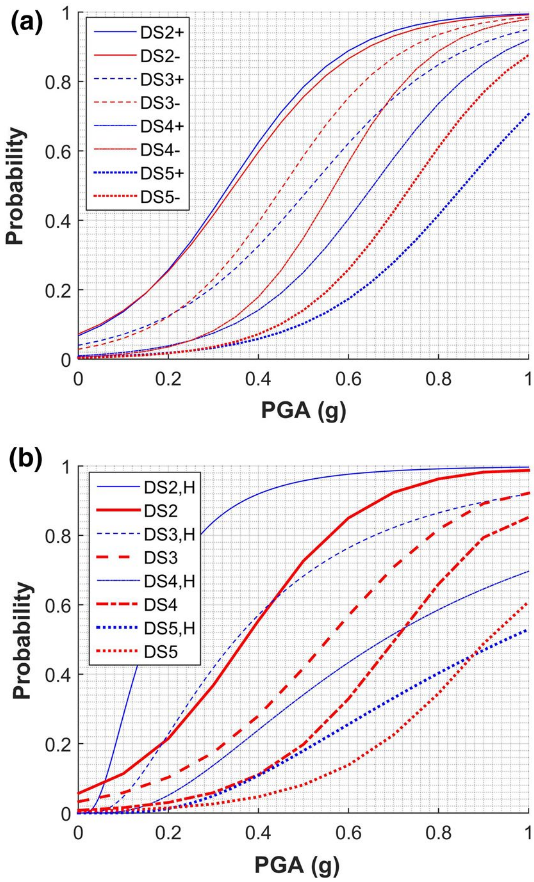

Fig. 2 **a** Effect of FEA results to fragility curves, **b** Comparison with HAZUS curves

In addition, different statistical methods were used for curve fitting to the data called "observation frequency" of the damage. The main conclusions in this research are as follows:

(1) Fig. 2a shows the fragility curves created using the database where finite element analysis (FEA) results are included and not included for all damage states. In the graph, the blue curves show cases where FEA results are included, and red curves show cases where FEA results are not included.

(2) In Sect. 2, the number of assignments of tanks to damage states are given as a result of FEA. In both cases, the curves were sensitive on the total number of tanks, whereas no changes for high damage states can be detected. In other words, the results of FEA show that the tanks do not display high damage states at high PGA values. That is the reason why the curves separated from each other.

(3) In Fig. 2b, comparison graphs with HAZUS fragility curves are given. As stated at the end of the previous section, differences in the curves are acceptable. The similar differences are also observed in Fig. 3.

(4) The points expressing the "observation frequency" values for each damage state show significant changes after approximately 0.5 g. The reason for this is that in analytical studies, no significant damage occurs in tanks at high PGA values. However, it is observed here analytical studies change the probability of damage. In the figures, the blue points show cases where FEA results are included, and red points show cases where FEA results are not included.

(5) In Fig. 4, the curves are obtained by using the statistical curve fitting methods. The curve obtained using the lognormal distribution model yields more separated results than the curves obtained by the other methods. The reason for this is that the observation frequency points are not distributed regularly and scattered irregularly. Curves produced by the logit model, the probit model, and the maximum likelihood method gave close results.

(6) In the future studies, it is aimed to increase the existing information on the parameters such as tank physical properties, liquid filling level, anchorage status, roof type with analytical studies and to produce new curves for these parameters.

(7) It has been seen how analytical studies containing relatively few data compared to the database based on observation, still affect the results. The study produces more realistic data and curves by adding accurate analytical study results.

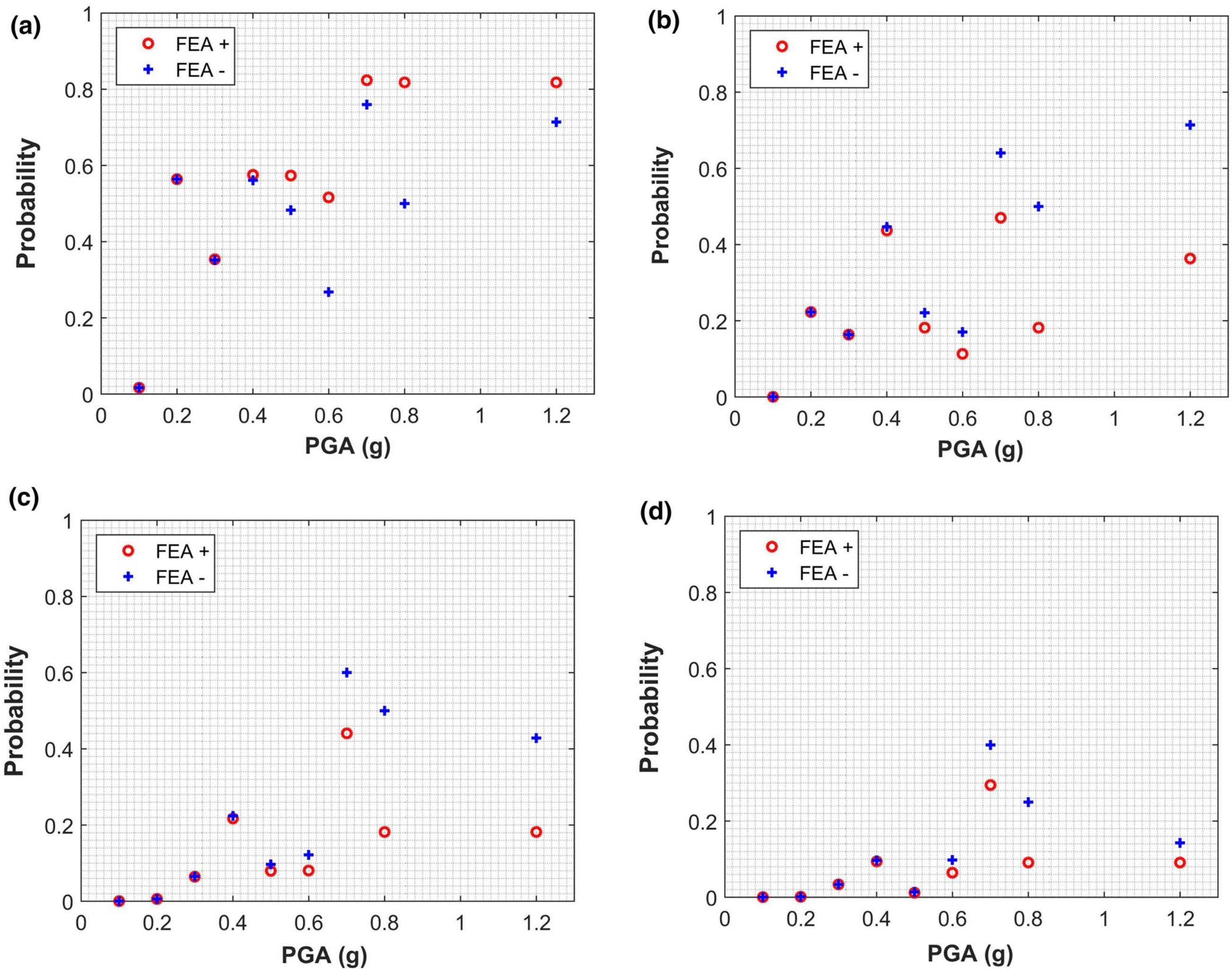

Fig. 3 Effect of FEA results to **a** DS2, **b** DS3, **c** DS4, **d** DS5 observation probabilities

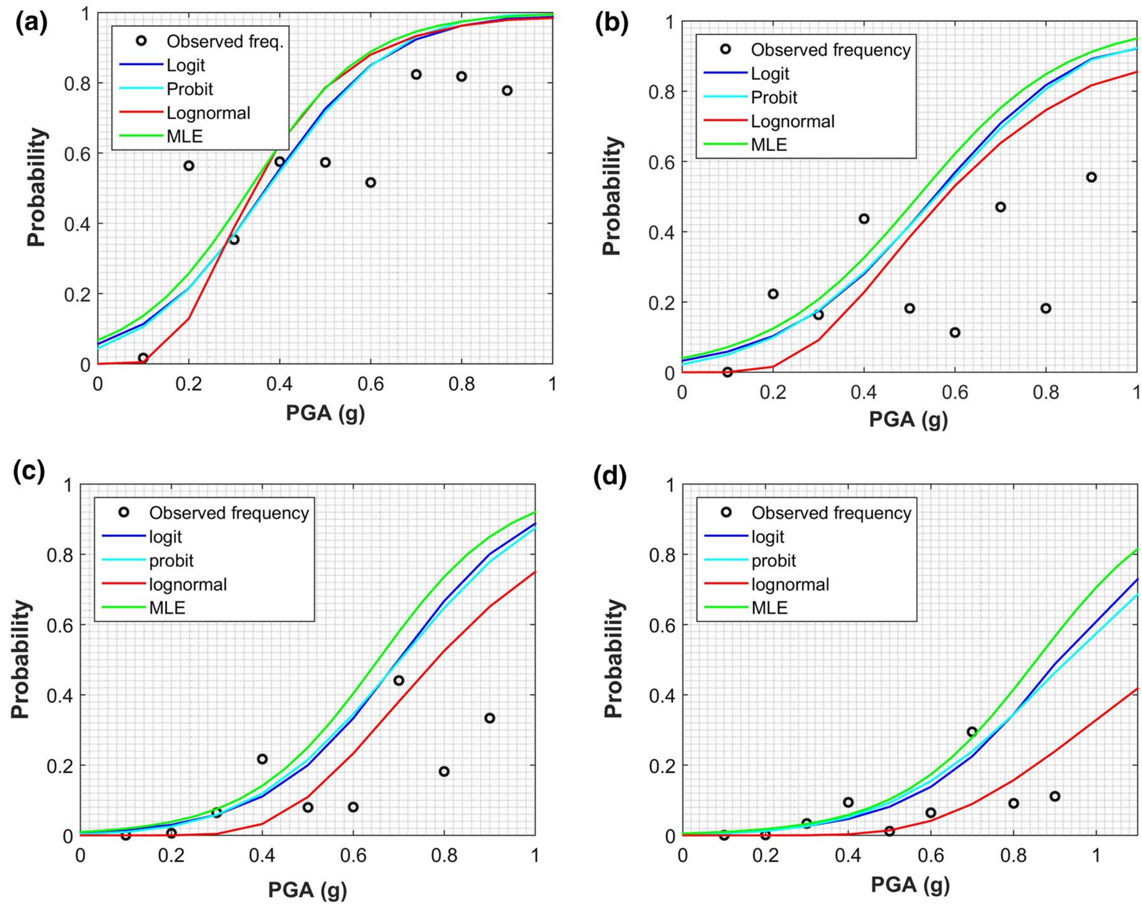

Fig. 4 Effect of fitting methods to **a** DS2, **b** DS3, **c** DS4, **d** DS5 curves

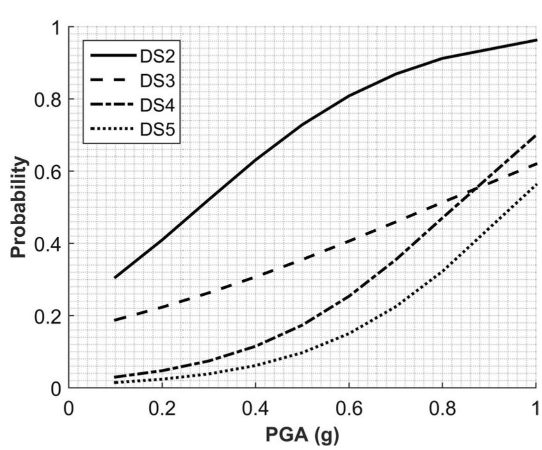

Fig. 5 Fragility curves of the fixed roof tanks

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