Development of Analytical Fragility Curves for Cylindrical Steel Oil Tanks

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ABSTRACT:
Aboveground cylindrical liquid storage tanks are important components of industrial plants especially oil refineries and petrochemical facilities. Performance of liquid storage tanks during the past earthquakes showed that these structures are seismically vulnerable. For this reason the evaluation of seismic vulnerability of existing liquid storage tanks is an important task in high seismic risk zones of the world.
Seismic performance functions (such as fragility curves) are useful tools in order to quantify seismic vulnerability of structures. These functions formulate loss or probability of occurrence or exceeding of damage state in terms of seismic hazard level. There are at least four approaches for development of seismic fragility functions: judgmental, empirical, analytical and hybrid methods.
The purpose of this study is development of seismic fragility curves for on-ground steel oil tanks based on analytical and empirical approach. For this purpose, existing liquid storage tank of one of the Iranian oil refineries selected and modeled by using FEM. Nonlinear time-history analysis carried out to estimate seismic performance of tanks of different height to diameter (H/D) ratios and different volume of contained liquid (%full). The seismic fragility curves of oil storage tanks developed by using the results of numerical analyses. The seismic fragility curves, developed herein presented in terms of H/D ratio and % Full and compared to available seismic fragility curves of cylindrical steel tanks.
The results of this study showed that H/D ratio and % full are major sources of uncertainty in seismic fragility curves of cylindrical steel oil tanks. It has also shown that improper distribution of tanks in the earthquake affected area may cause noticeable dispersions in empirical fragility curves.

KEYWORDS:
Fragility Curves, Cylindrical Tank, Seismic Performance

1. INTRODUCTION

On-ground cylindrical tanks are important components of many industrial plants. Damage to cylindrical steel tanks during the past earthquakes revealed that they are seismically vulnerable. Hence, seismic safety evaluation of the existing oil storage tanks is an important task in high seismic risk zones. A fundamental requirement for assessing the seismic performance of cylindrical steel tanks is the ability to quantify the potential for damage as a function of the level of seismic hazards (e.g. PGA). Fragility curves relate strong motion severity to the probability of reaching or exceeding a certain limit state.
There are several seismic fragility curves available for liquid storage tanks. ATC 13 (ATC, 1985) and HAZUS (NIBS, 1999) developed judgmental seismic fragility curves for cylindrical steel tanks. The advantage of these fragility curves is that they developed based on the opinions of several experts. But the main shortcoming of such curves is that they depend on the experiences of the individual experiences of the experts and there is a large scatter among the opinions of different experts. Based on the performance of the tanks during the occurred earthquakes, O'Rourke and So (O'Rourke, 2000) and ALA (ALA, 2001, 2001a) developed empirical fragility curves. The main limitation for empirical fragility curves is dependency of the reliability of these curves to the accuracy of the data recorded in databases. Hence inaccurate damage classification, variation of the level of the contained liquid and quality of construction may cause dispersion or error in empirical fragility curves. Moreover the numbers of the earthquake affected tanks during the past earthquakes are limited compared to the framed structures and this may cause reduction in the accuracy of the results.
Another shortcoming for the available seismic fragility curves of the liquid storage tanks is that in these fragility

curves there is no care either on the type of roof or on the kind of contained liquid. In other words, for every type of roofing system (e.g. floating or fixed) and for every kinds of fluid (e.g. oil, water, molasses) only one curve is presented for each type of anchored and unanchored tanks.
Analytical approaches are useful methods to overcome the shortcomings of judgmental and empirical curves. By using this approach, one can estimate damage distributions for specific known volume of contents, site specifications and so on. Through the knowledge of the authors, there is no well-known analytical fragility curve for liquid storage tanks.
This study aims to demonstrate that height to diameter ratio (H/D) and %full are important sources of uncertainty in available fragility curves.

2. NUMERICAL ANALYSIS

In this study nonlinear dynamic time-history analysis is considered to estimate the seismic performance of liquid-storage tanks. The three-dimensional liquid-tank models were used. The tanks were simulated by using a multi-purpose FEM code. Elements capable of modeling material as well as geometric nonlinearity were used for modeling of the system. An elastoplastic bilinear model considered to simulate the nonlinear behavior of steel in shell, roof and base plate. An assumption was made that all of the tanks are resting on rigid foundations. In order to perform numerical analyses, five categories of tanks were selected. The selected tanks were of cone roof type with different aspect ratios. The geometric specifications of the tanks are shown in table 1. In this table “D” denotes tank diameter, “H” denotes shell height, “tr” and “tb” denote thickness of roof and base plate respectively and “nc” is the number of shell courses. As indicated in table 1, the aspect ratios (H/D) of selected tanks were varied from 0.3 to 1.0 (H/D= 0.3, 0.4. 0.5, 0.6 and 1.0) which contain both broad and tall tanks. The density of contained liquid was assumed to be 8 kN/m3. The modulus of elasticity of steel shell was considered to be 210 GPa, The Poisson's ratio density and yield stress assumed to be 0.3, 78.5 kN/m3 and 240 Mpa, respectively. It is worth mentioning that all of the selected tanks were located in an existing large oil refinery in Iran.

Table 1. Geometric specifications of selected tanks

Tank	H (m)	D(m)	tb (mm)	tr (mm)	nc	Range of Shell Thickness (mm)
T3	14.75	43.8	6	5	6	8-25
T4	14.75	33.5	6	5	6	6-18
T5	14.75	27.5	6	5	6	6-12
T6	12.25	19.5	6	5	5	6-12
T10	7.35	7.6	6	5	3	6

In order to consider the effects of the volume of content, for each of the tank categories five different situations (h/H=0.2, 0.5, 0.7, 0. 8, 0.9) were considered where “h” is the height of contained liquid. Thus 25 finite element models were prepared for estimating the seismic demand of the tanks.
Three sets of strong ground motions representing low, moderate and long epicentral distances were used for investigating the seismic performance of the tanks. Since it was assumed that all of the tanks were rested on rigid foundations, all of the ground motions were selected among those recorded on stiff soil or rock sites. The specifications of the selected ground motions are summarized in table 2. All of the records were normalized to a range of 0.2g to1.0g in steps of 0.2g.

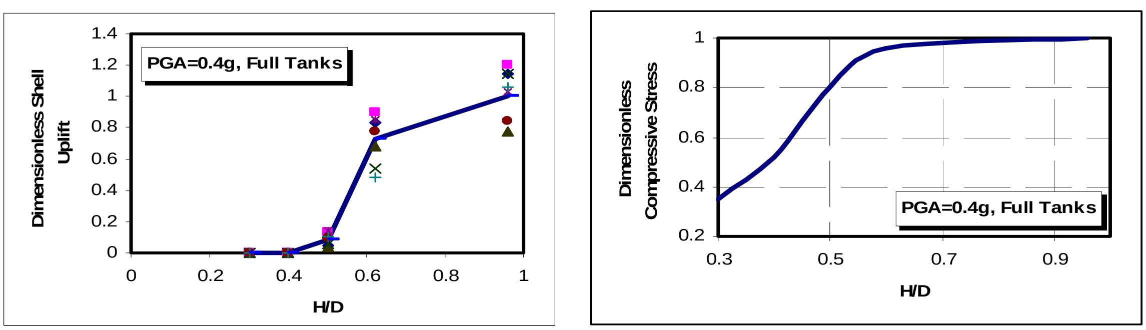
Table 2. Specification of Selected records

Set	Event	Date	L (Km)	Magnitude
GS-1	Tabas	1979	3	7.4
	Northridge	1994	3.9	6.7
	Loma-Prieta	1989	5.1	6.9
GS-2	Izmit	1999	17	7.4
	Chi-Chi	1999	24	7.6
	San-Fernando	1971	24.2	6.6
GS-3	Mexico	1980	35	6.4
	Kern County	1952	42	7.4
	Manjil	1990	49	7.4
	Landers	1992	51.3	7.3

1.1. Results of Numerical Analyses

Nonlinear time-history analyses performed to investigate the dynamic performance of the tanks by using a multipurpose finite element code, (Razzaghi, 2007). A brief review to results of numerical analyses is presented herein. However, the results of numerical analyses are presented in (Razzaghi, Eshghi, 2006), (Eshghi, Razzaghi 2006) in detail.

Results of numerical analyses revealed that there is obvious differences between seismic performances of tanks with aspect ratios of greater than or equal to 0.6 with broader tanks. For instance the maximum shell uplift of the tanks due to each of the input motions with constant PGA is increases by increasing the aspect ratio. Figure 3 illustrates the variation of the shell uplift as well as maximum shell compression due to various input motions versus H/D ratio. The peak ground acceleration of the input motions in Figure 1 is PGA=0.4g. The same charts are available for other values of PGA in (Razzaghi, 2007). As indicated in figure 1, the average shell uplift of tanks of H/D<0.6 is considerably less than the other tanks. Moreover the mean value of maximum shell compression in tanks of H/D>0.5 is greater than tanks of H/D<=0.4



(a) (b)

Figure 1 Variation of the response of the tanks by aspect ratio (a) shell uplift (b) axial compression in shell

2. DEVELOPMENT OF FRAGILITY CURVES

Fragility curves of the tanks were developed by using results of more than 600 numerical analyses. In this study peak ground acceleration (PGA) was used to characterize the ground motion. Hence each point of a fragility curve represents the probability of exceeding each damage state for a certain PGA. For each case, this probability can be calculated by dividing the number of damaged tanks to total number of analyzed tanks.

Herein the Fragility curves for two damage states of D2 and D3 are developed. The fragility curves for other damage states are presented in (Razzaghi, 2007). The damage states D2 denotes occurring plastic deformations in shell and roof without any elastic-plastic buckling. The damage state D3 represents Elephant-foot buckling without failure of pipes. These damage states are equivalent to DS2 and DS3 damage states in HAZUS and O'Rourke fragility curves. The damage state D2 defined as exceeding the shell and/or roof stresses from yielding stress without the exceeding of the compressive stress from the elastic-plastic buckling capacity. For this purpose the Von-Myses failure criterion was considered. The damage state D3 defined as exceeding the compressive stress from the elastic-plastic buckling capacity. An attempt was made that in none of the buckled tanks failure of connecting pipes occurred. The elastic-plastic failure was checked by using Rotter (Rotter, 1985) analytical relation which is recommended by (NZSEE, 1985) and Eurocode 8 (ENV, 1999) as an elastic-plastic capacity of the shell. In order to investigate the effects of geometric specifications of the tanks on their seismic performance, for each category of tanks a specific fragility curve was developed. In order to neglect the contribution of %Full, only full tanks were taken into account in development of these curves. It is worth mentioning that in this study tanks with h/H=0.9 considered as full tanks. This consideration is because of the freeboard requirements of the contained liquid.

Figures 2 and 3 indicate developed fragility curves for full tanks with different aspect ratios. The term "all tanks" in these figures represents all of the existing tanks of the tank farm in the scope of this study. As indicated in figures 2 and 3 there is an obvious difference between fragility curves of broad and tall tanks. Furthermore, curves which were developed for all tanks are far from fragility curves of both broad and tall tanks. In other words, aspect ratio (H/D) of the tanks is an important source of uncertainty in seismic fragility curves of liquid storage tanks. Hence those fragility curves that were developed based on the seismic performance of all of the tanks of different aspect ratios are not proper curves for estimating the fragility of either broad tanks or tall ones. It has also shown that the fragility curves of tanks with aspect ratios of 0.3 and 0.4 were the same for almost all of the damage states. The only exception is the damage state D3 within the PGA range of 0.4g to 0.8g. Moreover, tanks of categories T6 and T10 (H/D= 0.6, 0.9) have almost the same fragility curves for each damage state except D4. Hence the abovementioned figures seem to indicate that tall tanks (H/D>=0.6) have almost the same fragility curves. In addition the same fragility curves can be developed for very broad tanks (H/D<=0.4). Such a fact was intelligently recognized by O'Rourke and So (2000) according to the empirical data.

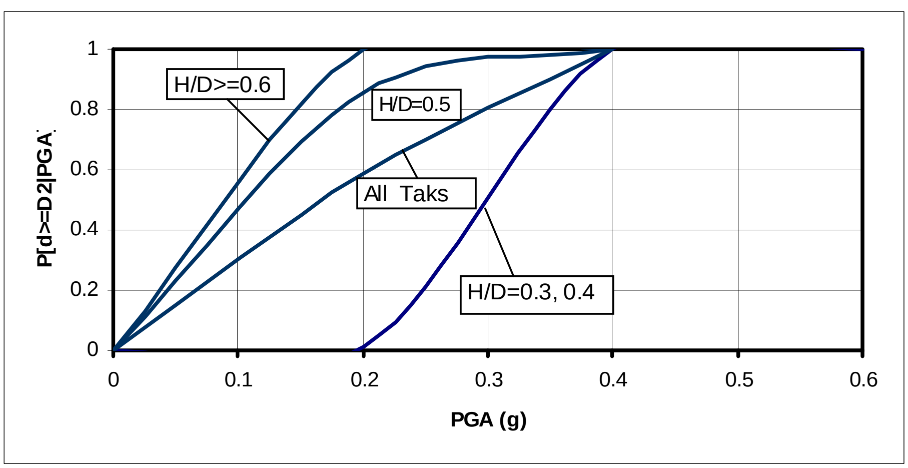


Figure 2 Seismic fragility curves of full tanks for damage state “D2”

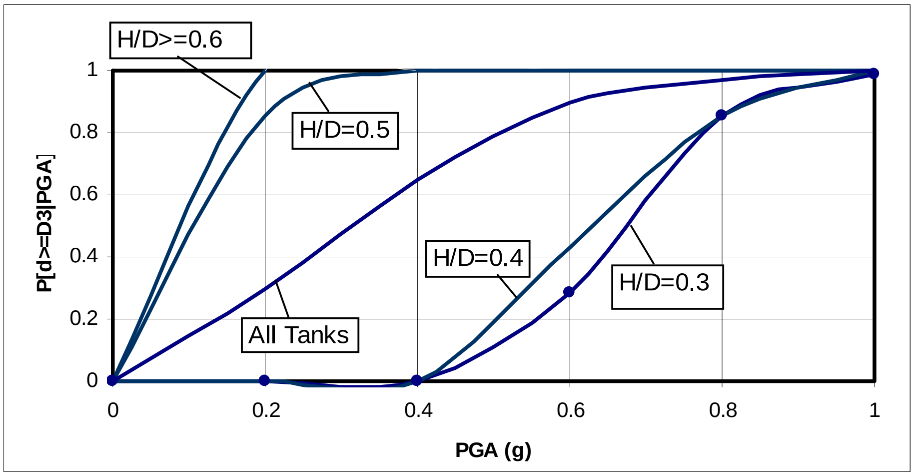


Figure 3 Seismic fragility curves of full tanks for damage state "D3"

In order to investigate the effect of volume of content on seismic fragility of the tanks, the fragility curves of all of the tanks were developed for three different cases: full tanks, 50% and 70% full tanks. The comparison of these fragility curves for damage state "D2" is shown in figure 4. The dispersion of the results for each category of tanks was noticeable. This happened because of insufficient number of data for each category of tanks. Hence, the fragility curves of "all tanks" are presented herein. In order to develop seismic fragility curves for each category of tanks and the other damage states, more numerical analyses are required. As indicated in this figure there is a large scatter among the results of fragility analysis with different volumes of content for PGAs greater than 0.2g and less than 0.7g. The maximum difference between the probability of failure in full and 50% full tanks is 56% which related to PGA=0.4g.

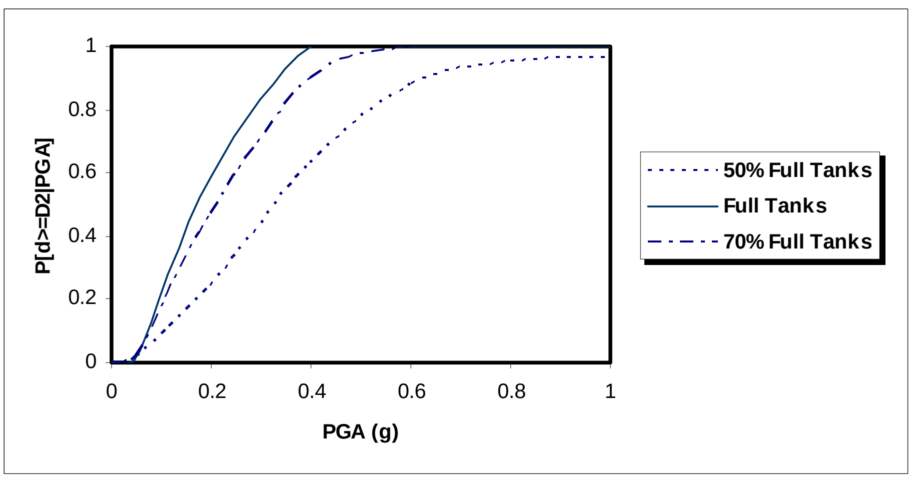


Figure 4 The effect of % full on seismic fragility of all tanks for damage state "D2"

3. COMPARING THE RESULTS TO EMPIRICAL DATA

During the last decade several tanks experienced strong ground motion (Eshghi, Razzaghi, 2005, 2006). Some of these tanks suffered minor to moderate damage. A database of performance of tanks during three major earthquakes was developed (Razzaghi, 2007). This data obtained from visual inspection of about fifty unanchored cylindrical liquid storage tanks following the seismic events. The number of inspected tanks and the PGA range that each of tanks experienced are presented in table 3.

Table 3 Specifications of inspected tanks following the earthquakes

Event	Year	Number of Tanks	Roof Type	PGA Range (g)
Bam	2003	1	Fixed	0.7
		6	Fixed	0.44-0.6
Zarand	2005	11	Fixed	0.16-0.25
Silakhor	2006	7	Fixed	0.44
		12	Fixed	0.16-0.25
		8	Fixed	0.09-0.15

Most of the damaged tanks experienced damage state D2 and only one of them suffered damage state D3. None of the affected tanks suffered major damage. The probability of occurrence or exceeding the damage state D2 for the affected tanks during the earthquake for all of the tanks (either broad or tall) calculated and compared with analytical fragility curves developed herein (See Figure 5). As indicated in figure 5 the probabilities of failure which were estimated using empirical data are less than the values of the fragility curve of full tanks. It has also shown that empirical probabilities are less than seismic fragility of the full tanks. The empirical data are more close to the fragility curve of 50% full tanks. This happened because most of the tanks in abovementioned database were about 50% full during earthquakes. Figures 4 and 5 seem to indicate that seismic fragility curves of full tanks can be considered as the upper bounds the fragility curves of the tanks.

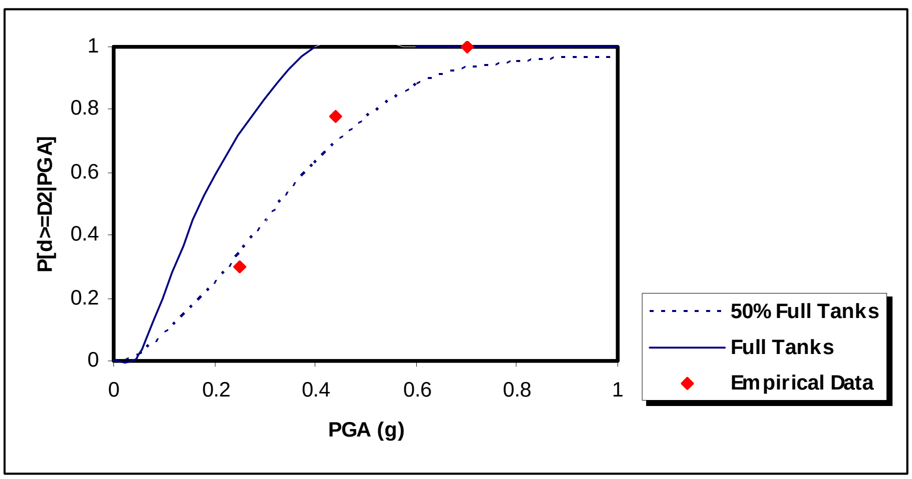


Figure 5 Comparing the analytical fragility curves with empirical data

4. COMPARING THE RESULTS TO AVAILABLE FRAGILITY CURVES

HAZUS (NIBS, 1999) developed a single judgmental fragility curve for "all tanks" in each damage state. O'Rourke and So (2000) presented three empirical fragility curves for tanks in each damage state: tanks of H/D>0.7, tanks of H/D<0.7 and "all tanks". As mentioned before, in this study analytical fragility curves for different categories of tanks as well as "all tanks" were developed. Hence in order to compare the above mentioned fragility curves to each other, those curves which were developed for "all tanks" were considered. Note in this regard that the analytical fragility curves are related to all of full tanks which can be considered as the upper bound of fragility curves for "all tanks". The comparison of these fragility curves for different damage states are indicated in Figures 6 and 7. As shown in these figures there is a large scatter within judgmental, empirical and analytical fragility curves. It seems that the main reasons for such differences are uncertainties associated in the fragility analysis. As demonstrated before, aspect ratio and %Full are two of the important sources of uncertainty in fragility analysis of the unanchored tanks. In addition, the dynamic behavior of liquid storage tanks is related to structural configurations, physical properties of the liquid, etc. Thus variation of each of these specifications may cause noticeable changes in seismic performance of the tanks. Hence, when a single fragility curve is developed for all categories of tanks; a great uncertainty is imposed to the fragility analysis. Figures 6 and 7 seem to indicate that the O'Rourke fragility curves can be considered as lower bounds for seismic fragility curves of "all tanks".

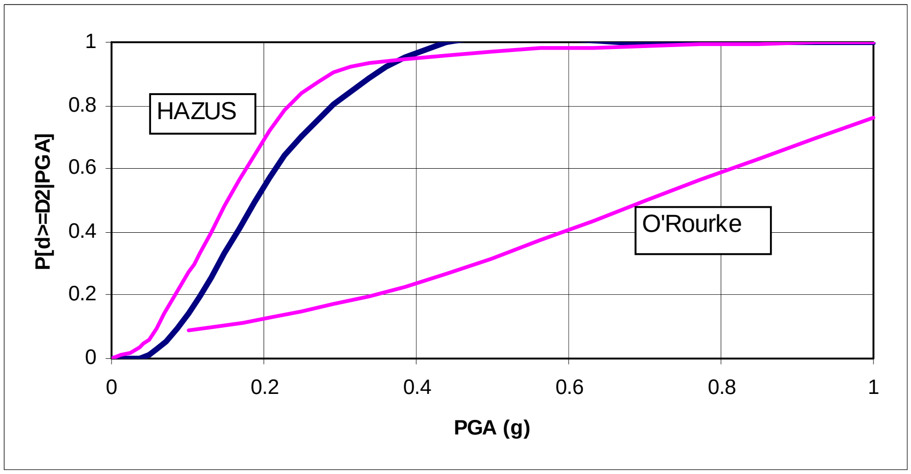


Figure 6 Comparison of analytical fragility curves with HAZUS and O'Rourke curves for damage state "D2"

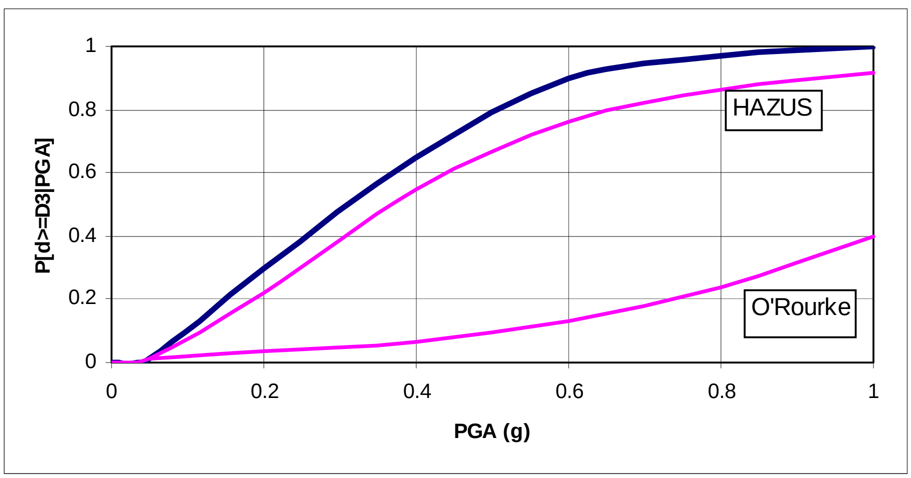


Figure 7 Comparison of analytical fragility curves with HAZUS and O'Rourke curves for damage state "D3"

4. CONCLUSIONS

Analytical seismic fragility curves were developed for unanchored steel oil storage tanks. Non-linear dynamic time-history analysis conducted, by using the records of ten real earthquakes. This study focused on the effects of the aspect ratios and volume of contained liquid on seismic fragility curves of the unanchored tanks. The effects of these two parameters were taken into account by considering five different aspect ratios (H/D= 0.3, 0.4. 0.5, 0.6 and 1.0) as well as five different liquid contents (h/H=0.2, 0.5, 0.7, 0. 8 and 0.90). It was shown that the height to diameter ratio and the volume of the contained fluid have great effects on seismic vulnerability of unanchored oil storage tanks. The fragility of tanks increases with the aspect ratio. Moreover, the fragility curves of the full tanks can be considered as an upper bound for seismic fragility of "all tanks". However, more analyses are required for concrete conclusion about the effects of %Full on seismic fragility of each category of tanks especially about tall tanks.

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