SEISMIC VULNERABILITY ANALYSES OF STEEL STORAGE TANKS IN AN OIL REFINERY COMPLEX USING DYNAMIC ANALYSES

N. Hosseinzadeh

Assistant Professor, Dept. of Structural Engineering, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, *Email: hosseinz@iiees.ac.ir*

ABSTRACT :

Cylindrical steel above ground tanks extensively used in oil refinery complexes and oil depots in Iran. Average capacity of this kind of tanks is about 20,000 kl with diameter of about 40 m and height of about 14 meter. Past earthquake experiences in Japan, U.S. and turkey show that these tanks are very vulnerable to strong ground motions. Failure modes such as settlement, shell buckling, Roof Damage and overturning are the main causes of extensive material leakage and fire immediately after an earthquake. In this paper 181 tanks in an oil refinery complex are categorized into 30 types in order to seismic vulnerability evaluation and retrofit design. International documented references such as new revisions of API650 and ASCE standards and Finite Element Method is used in this study. Important parameters such as Liquid sloshing, tank bottom uplift and liquid-shell interaction considered in dynamic analyses. Site-specific spectrum, as well as site compatible earthquake records considered as input motions. The results show that about 60 percent of the existing tanks are vulnerable and require retrofitting or strengthening.

KEYWORDS: Seismic Vulnerability, Steel Storage Tanks, Oil Refinery Complex, Retrofitting, Failure modes

1. INTRODUCTION

The dimension of modern oil and liquid fuel storage tanks in refineries and oil depots varies from 12 to 76 m (40 to 250 ft) in diameter with height that are nearly always less than the diameter. Ground supported tanks can be classified as anchored or unanchored tanks depending on their support conditions [1]. Ground supported, circular cylindrical tanks are more frequent than any other types because they are simply in design, efficient in resisting primary hydrostatic pressure, and can be easily constructed.

The vulnerability and seismic risk level of above ground liquid tanks are very high. These components during seismic events have implications far beyond the more economic value of them and their contents. If, for instance, a water tank collapses, as occurred during the 1933 Long Beach and the 1971 San Fernando earthquakes, loss of public water supply can have serious consequences. Similarly, failure of tanks storing combustible materials, as occurred during the 1964 Niigata, Japan, the 1964 Alaska earthquakes, can lead to extensive uncontrolled fires. The Tupras refinery fire imidiately after the 1999 Kocaeli earthquake is another example of seismic vulnerability of above ground oil tanks.

Due to the complexity of the problem, most of the original studies about the seismic behavior of anchored and unanchored tanks were experimental in nature. Several simplified theoretical investigations were also conducted and a few of these studies have been used as a basis for current design standards. Yet, the large-scale damage to unanchored tanks in recent earthquakes highlighted the need for a careful analysis of such tanks.

The objective of this paper is to evaluate the seismic vulnerability of cylindrical liquid storage tanks of an Iranian refinery oil complex according to International documented standards and guidelines [2, 3]. Finite element analyses (FEM) have been made in order to vulnerability evaluation and retrofit design of studied tanks.

2. FAILURE PATTERNS OF STORAGE TANKS

Earthquake damages of cylindrical steel above ground tanks can be observed in several patterns. Large axial compressive stresses of tank shell can cause elephant-foot buckling due to the seismic overturning forces. Sloshing of the liquid near the free surface can damage the roof and upper shell of the tanks. High stresses in vicinity of poorly detailed base anchors can rupture the tank wall. Base shears can overcome the base friction causing the tank to slide. Base uplifting can cause several damages such as damage the piping connected to tank that are incapable of accommodating large vertical displacements, rupture the base plate-mantle junction due to excessive joint stresses, and uneven settlement of the foundation. Important failure modes of steel above ground tanks are: 1) Overturning, 2) Elastic buckling, 3) Sliding, 4) Elasto-Plastic buckling (Elephant foot buckling), 5) Tank roof damage, 6) Uplift, 7) Different settlement. A complete description of these 7 failure modes have been discussed in reference [4].

3. TANKS INFORMATION

As mentioned above, 181 tanks in an oil refinery complex considered for detailed seismic vulnerability analyses. These tanks divided in 30 different types. Dimensions and mechanical properties of tanks in each type are similar. General information of these tanks including diameter, capacity, height, shell thicknesses, roof type, and base anchorage is summarized in table 1. All required Information are obtained from document center of oil complex. For this purpose, all structural drawings and documents, geotechnical reports, material specifications, and construction details have been studied.

Table 1 General tanks information for detailed analyses

tank's ID			tank's geometry				fluid content	base support	roof system
row	type	type	capacity	height	liquid level	diameter	special density		
No.	name	No.	m3	mm	mm	mm	ton/m3		
1	RT6	01001	65.4	6550	6250	3700	1.025	anchored	cone roof
2	RT5	20261	54	4595	4200	3872	0.82	anchored	cone roof
3	RT4	52001	31	2500,3	2200	4000	1.236-1.508	anchored	floating roof (SD)
4	RT3	52003A	80	5486	5100	4300	1.074	anchored	cone roof
5	RT2	52004A	80	5486	5100	4300	1.261	anchored	cone roof
6	RT1	26001	68	4575	4275	4370	1.84	anchored	cone roof
7	RQ	22101	800	9114	8580	10668	0.992	anchored	cone roof
8	RP	59001	612	6560	6060	10900	1.8	unanchored	dome roof
9	RO	51002	1221	8300	7800	13690	1.84	unanchored	cone roof
10	RN	23001A	1650	11200	10800	13700	1.02	anchored	cone roof
11	RM	20216	2390	9780	9280	17640	0.887	unanchored	cone roof
12	RL	20206	3180	12205	10805	19360	0.802	unanchored	dome roof
13	RK	20126	3980	12205	10805	21660	0.743	unanchored	floating roof (DD)
14	RJ	20224	4770	12200	11705	22310	1.06	unanchored	cone roof
15	RI	20148	4770	12205	10805	23710	1.025	unanchored	floating roof (SD)
16	RH	20136	7950	14630	13230	27700	0.804	unanchored	floating roof (SD)
17	RG	20141	12720	14630	14130	33300	0.835	unanchored	cone roof
18	RF	20212	12720	14630	13230	35100	0.82	unanchored	floating roof (SD)
19	RE	20108	15900	14630	14130	37200	0.814	unanchored	dome roof
20	RD	20114	15900	14630	14130	37200	1.084	unanchored	cone roof
21	RC	20129	15900	14630	13230	39200	0.82	unanchored	floating roof (SD)
22	RB	20102	23850	14630	14130	45600	0.754	unanchored	dome roof
23	RA	20001	79500	14630	13230	87500	0.871	unanchored	floating roof (SD)
24	DA	101	5970	12802	11975	24384	1.06	unanchored	cone roof
25	DB	153	12720	14630	13230	35100	0.82	unanchored	floating roof (SD)
26	DC	191	21470	14631	13871	43892	0.72	unanchored	floating roof (DD)
27	DD	161	41330	18300	17000	53646	1.02	unanchored	cone roof
28	DE	175	40290	18288	17088	53645	0.84	unanchored	floating roof (DD)
29	PA	22101	800	9114	8580	10668	0.992	anchored	cone roof
30	PB	23001A	1650	11200	10800	13700	1.02	anchored	cone roof

4. ANALYTICAL APPROACH

According to the tanks failure modes, refined analytical models are necessary for seismic vulnerability evaluation of tanks. Dynamic analyses of typical tank models subjected to site-specific seismic loads using FEM, is considered for analyses and retrofitting design. Based on the risk analyses, Horizontal Peak Ground Acceleration (HPGA) of 0.40g is considered for seismic evaluation based on the 10% probability of exceedance in 50 years. Site-specific acceleration response spectra shown in Figure 1, as well as 3 site compatible earthquake records (Tabas, Sarkhoon, and Zangiran) are considered as input ground motions for dynamic analyses. Acceleration time history of Tabas record as one of the input ground motions is shown in Figure 2.

Finite element program is used in this study [5]. Refined models for tank analysis are considered using fluid elements and fluid-structure interactions and only compression link elements. The system of tank roof is considered as shell and beam elements, which are placed in the radial and circular directions. The tank wall is modeled by shell elements. The contents of tanks are modeled by fluid elements. The fluid elements at the wall boundary are not attached directly to the shell elements. Coincident nodes considered in these locations that are coupled only in the normal direction to the interface. Relative movements in the tangential and vertical directions are allowed to occur. Fluid element nodes at the base are allowed to move on the surface of the tank bottom plate.

Linear elastic small deformation analysis is performed for modal analysis. The significant natural modes considered by comparison of the participation factors, modal coefficients, and mass distribution percentages for each mode extracted. Larger mass distribution percentages usually indicate important modes in the corresponding dynamic response analysis. The number of modes considered in spectral analysis is based on achievement of 90% seismic structural mass.

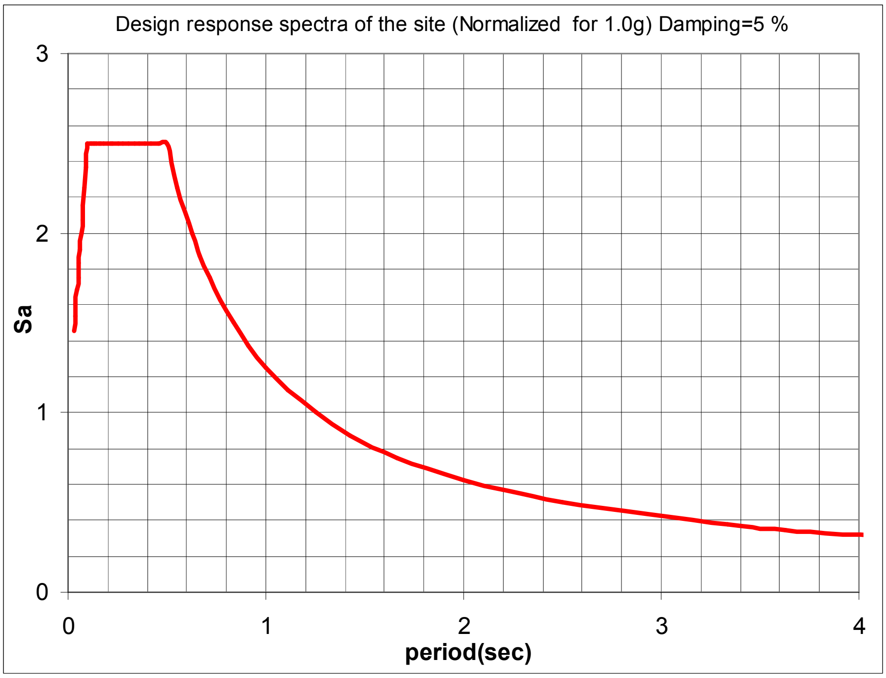


Figure 1 Normalized site-specific response spectra for design earthquake

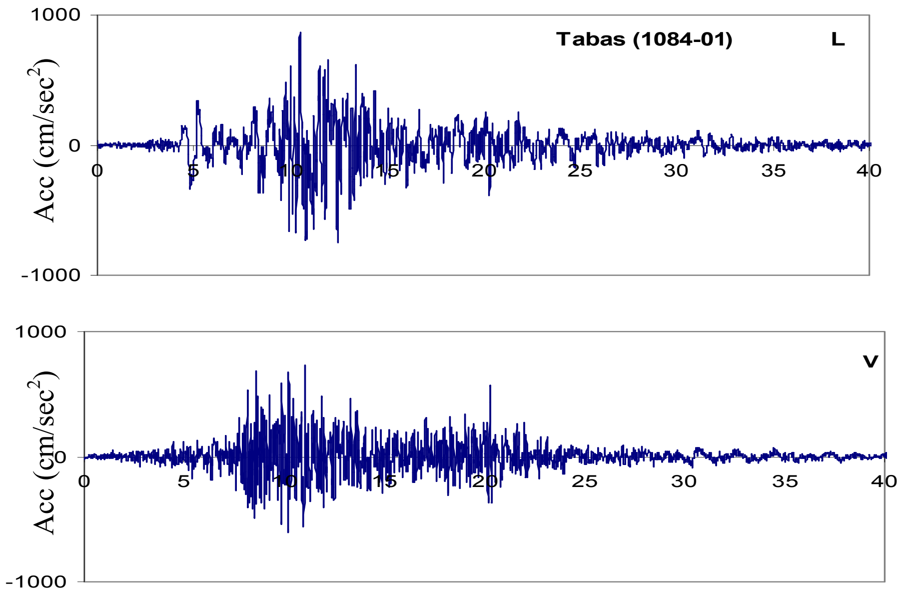
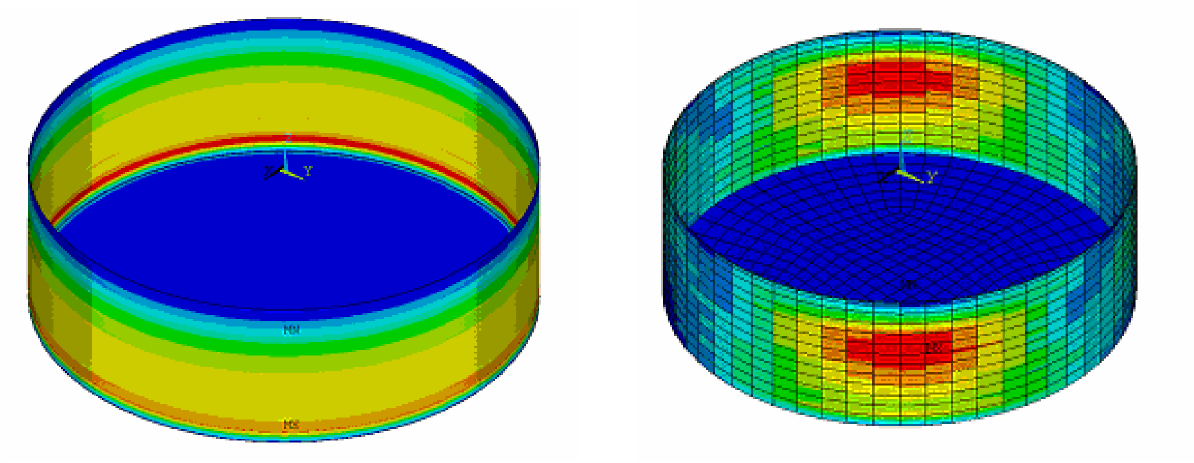


Figure 2 Horizontal (L) and vertical (V) component Tabas record

5. ANALYSES RESULTS

The results of static and dynamic analyses of studied tanks are presented in this section. The first horizontal impulsive and convective mode frequencies for tank type 22 are 4.08 Hz and 0.172 Hz, respectively. These values are consistent with the theoretical values. Convective mode with low frequency (high period) tends to sloshing of fluid and tank roof damage The difference between impulsive and convective mode frequencies shows that interaction effects between these modes is not considerable.

An example of the Von-misses stresses of tank shell due to hydrostatic forces and spectral forces for tank type 22 is shown in Figure 2. Maximum static stresses are located in shell plates near the bottom plate. These stresses in the case of spectral forces are located in middle of shell plates.



(a) (b)

Figure 2 Von-misses stresses of tank shell due to a) hydrostatic forces and b) spectral forces

Sample displacement time histories of tank bottom uplift and fluid sloshing displacements for two apposite nodes due to the Tabas record for tank type 22 are shown in Figure 3 and Figure 4. Based on the results obtained from static and dynamic analyses, the vulnerability of studied tanks is investigated.

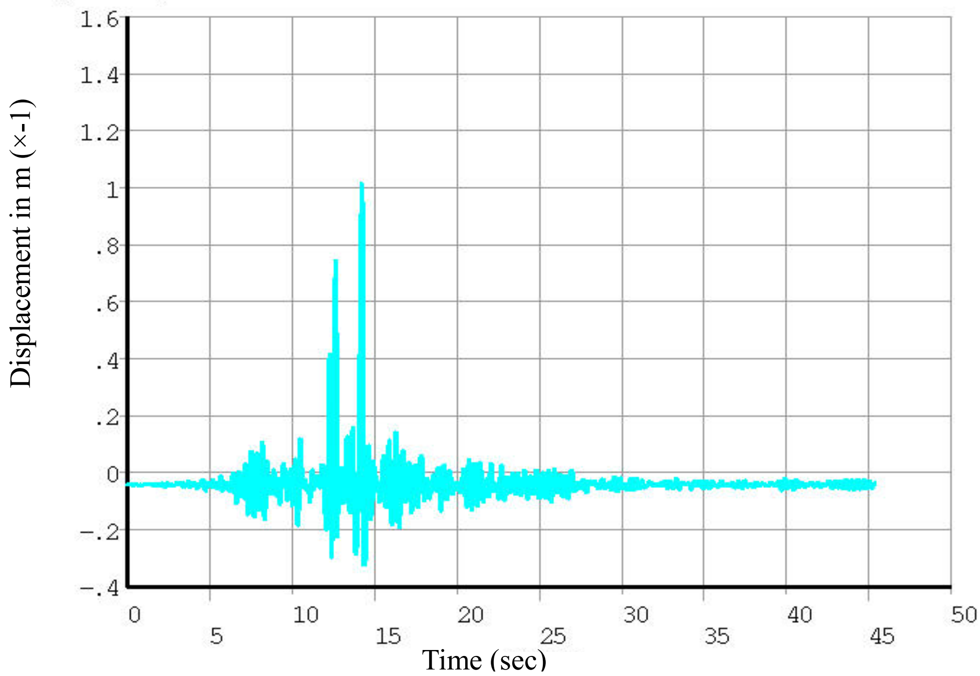


Figure 3 Uplift displacement time history of tank type 22 due to Tabas record

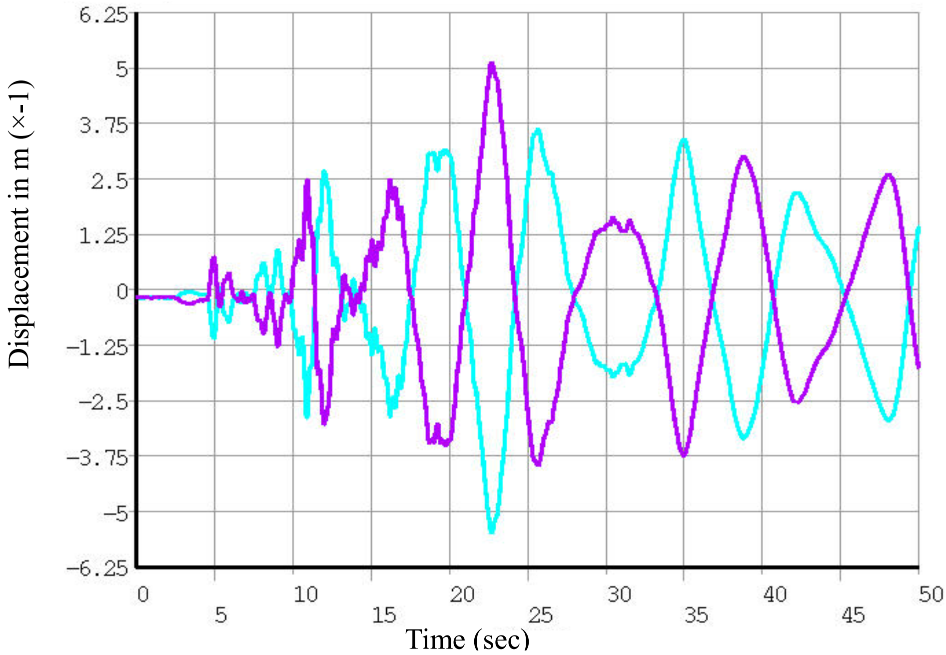


Figure 4 Sloshing displacements time history of tank type 22 due to Tabas record

6. VULNERABILITY ANALYSES

Based on the extensive and refined analyses performed for 30 types of studied tanks, the vulnerability results are summarized in Table 2. In this Table, vulnerability results are determined based on the number of tank types which specific failure mode is dominated.

Results show that the failure modes of different settlement, Tank roof damage, and uplift are dominant with 52, 36 and 20 percentage of vulnerability, respectively. Failure modes of elasto-plastic buckling and overturning are located in moderate vulnerability levels with 8 and 4 percent of occurrence, respectively. Elastic buckling and sliding of the studied tanks is in safe position. Therefore, different settlement can be considered as dominant failure mode of studied tanks. Total number of vulnerable tanks in the complex is about 60 percent of total tanks that required to retrofitting or strengthening. However, the results of vulnerability analyses and strengthening details reported to the owner.

Table 2 Summery of vulnerability analyses of studied tanks

No.	Failure mode	Percentage of vulnerability (%)
1	Overturning	4
2	Elastic buckling	0
3	Sliding	0
4	Elasto-Plastic buckling	8
5	Tank roof damage	36
6	Uplift	20
7	Different settlement	52

7. CONCLUSION

Seismic vulnerability analyses of anchored and unanchored liquid storage steel tanks in an oil refinery complex were presented in this paper. Refined finite element analyses method has been used for static and dynamic analyses of 30 different types of tanks categorized from total number of 181 tanks of the complex. It was observed that the response of unanchored tanks was dominated by the different settlement failure mode in 52 percentage of occurrence in studied tank types. Tank roof damage and uplift modes of failures are the next dominant modes with 36 and 20 percentage of occurrences in studied tank types, respectively. Generally, About 60 percent of the existing studied tanks are very vulnerable and require retrofitting and strengthening.

It seems that similar results and conclusions can be considered for similar industrial centers in the high seismic regions of the country, which were designed and constructed based on the older codes and standards. However, complete reports of vulnerability analyses and strengthening details for all investigated tanks in the complex were reported to the owner. Future research will also permit a greater understanding of the response of liquid storage steel tanks under various seismic loadings.

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