Stability of Cylindrical Oil Storage Tanks During an Earthquake

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***Abstract*— Seismic stability of oil storage tanks is very important as these tanks are used extensively in different national industries such as refineries, power plants and fuel storage facilities. Today many of these tanks, designed and operated with past standards, have a long life, thus with the progress made in seismic designs, it is necessary to examine the tanks with the latest international standards. In the present study, the seismic behavior of different tanks in five types with height to radius ratios (0.78, 0.9, 1.0, 1.3 and 2.0) examined by ANSYS and some of their malfunction mechanisms were evaluated such as elephant-foot buckling, diamond buckling, roof damaging by fluctuating fluid, slide, overturning, uplifting floor, bed asymmetric subsidence. Several analyses including static, modal and linear spectral and nonlinear time-history analyses carried out on the oil storage tank and obtained the results. Site-specific spectrum with maximum acceleration of 0.3g as well as site compatible earthquake records are considered as input motions. Finally, it is found that if 18% of tank height is assumed to be empty, fluid turbulences by earthquake wouldn't put the roof at any risk. Furthermore, for uncontrolled tanks with 1.5 height/radius ratio and over, overturning will happen.**

***Index Term*— Reinforcement, steel tanks, seismic vulnerability, elephant foot buckling, diamond buckling.**

I. Introduction

It is necessary to examine seismic vulnerability of oil storage tanks, designed and operated based on past standards, with the latest developments. Some horrible earthquakes in the past such as tank explosions in 1964 earthquake in Niigata, Japan [1] or tank firings at Tupras Refinery in 1999 Kocaeli earthquake show the importance of fuel tanks more than before [2]. In fact, oil –above- ground tanks are of the very important structures commonly used in oil refineries and other infrastructure industries. In fact, a tank is called above-ground when its floor relies on soil. A steel tank is built from three parts: body, floor and roof. Tank floor is a flat plate relied on compacted bed or expanded foundation and its roof, depending on the contents, is built as stationary and movable (fixed & floating). Huzner modeled the dynamic behavior of tanks for the first time, and it has become a base for designing constitutes. He stated that a free surface tank exposed to lateral dynamic acceleration affects the tank wall in two ways: (1) impulsive pressure and (2) convective pressure. Impulsive movement comes from turbulent fluid over the tank, and convective pressure is applied as a part of fluid moves at the bottom of tank consistent with the shell. In fact, frequency of impulsive movement is considerably lower than the frequency of convective movement, that is, this mode is stimulated in higher earthquake periods [3]. Ali-Elzeiny (2003), a professor and researcher at the University of California, presented an article called "Factors Affecting the Nonlinear Seismic Response of unanchored Tank". He examined the effects of hydrodynamic pressure of fluid on the shells of unanchored tanks during earthquake pulsation. He also concluded that building tanks on flexible foundations is more appropriate than on solid foundations, as the foundation softness extends the relocation period of tanks against hydrodynamic forces [4]. Martin Koeller and Peravin Malhotra (2003) published an article called "Seismic Evaluation of Unanchored Cylindrical Tanks" in which seven tanks were examined with different height to radius ratio. They stated that there is a close relationship between height to radius ratio and plastic rotation of tanks [5].

There are two closed-above-ground tanks, depending on support conditions: anchored and unanchored. Vertical movement of shell on surface has been prevented for an anchored tank, while an unanchored tank could get off the ground with vigorous shakings; therefore, its accurate dynamic analysis requires a nonlinear analysis.

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II. Failure Mechanisms of Tanks Guidelines For

There are several essential factors damaging cylindrical oil storage tank during earthquake incidents. Increased vertical compressive stress on shell due to the tank uplifting and its combination with cyclic tensile stresses from liquid hydrostatic pressure creates elephant-foot buckling in lower sheets of wall. Surface waves of liquid from earthquake vibrations are also the main reason of damage to the roof and upper layers of shell. Exceeding base shear from floor friction also vibrates the tanks. Uplifting floor also may damage the connected pipes, increase wall stress as well as asymmetric subsidence of foundation [4]. So the damages to tanks may be expressed in seven vulnerability criteria.

A. Overturning

It happens when the center of gravity is uplifted. It is controlled using the formula (1).

$$O = M \Big/ [D^2 (W_L + W_t)] \quad (1)$$

In this formula, M stands for Overturning moment(N-m), W_L for Content weight per unit length of medium and W_t for Wall sheet weight per unit length in terms of (N/m). According to the code, O should be less than 1.57, or the tank is inconsistent and will overturn [6].

B. Elephant foot Buckling (Elastic-plastic Buckling)

Such buckling occurs because the vertical compression stress is increased vigorously when overturning happens in the tank. In this case, combination of two circular tensile stress from liquid hydrostatic pressure and vertical compression stress create this buckling on the wall. Excessive increase in circular tensile stress on the tank wall could be used as a criterion to control elephant-foot buckling. The code defines the standard value of this buckling as φR_n in which φ is the strength reduction factor (0.9) and R_n is equal to the shell yield stress [6].

C. Diamond Buckling (Elastic Buckling)

Compression stresses on the walls cause buckling at the middle parts which is known as diamond buckling. Tanks with high height are usually harmed by such damage [6].

D. Tank Slide

It occurs when big shear force collides with low friction force. To control tank slide, base shear is considered as the driving force, and friction of tank floor with bed as the resistive force and, as ASCE recommended, safety factor of 1.5 has been used for the facilities. Also the friction factor of tank and bed has been calculated as 0.4. So is the code recommended formula (2) to control tank slide [3].

$$1.5V \leq 0.4W \quad (2)$$

In this equation W represents the weight of tank and its contents (in terms of Newton) and V is the base shear.

E. Roof Damage

Seismic shaking force vibrates the tank and its contents. Frequency of wave vibration (impulsive mode) occurs very lower than the frequency of wall vibration (convective mode) and it isn't affected by the wall vibration, as its amplitude goes beyond recording the frequency content. In this case, if the anticipations on relocating floating roof aren't consistent with the amplitude of surface waves, they throw out the damaged roof cover and contents of tank or damage some parts of the roof guards severely. Wave height is the control factor [3].

F. Uplifting Floor

If uplifting floor exceeds of standard 30 cm, it may rupture the tank wall or break its connection pipes [3].

G. Asymmetric Subsidence

As the tank floor is filled with 90% compacted soil, uplifting floor and its impact will subside the floor. The code will be limited to the maximum subsidence of 5 cm [3].

III. MODELING

To simulate the exact behavior of tanks during earthquake, ANSYS is used to model the shell and contents. Among the most important features of this software are its liquid element modeling and its interaction with structure element as well as modeling nonlinear behaviors.

Shell63 element used to model the shell and Fluid80 element is for the fluid. It is noteworthy that boundary of liquid elements are not synchronized exactly with the shell. Strict relations are defined between liquid and shell, and they are able to move relatively. Also the liquid and shell nodes can move independently at the floor. Figure 1 shows a 3D model of a tank and how to shade it. Shell63 element is a shell membrane–bending-element which has the ability to bear forces within and perpendicular to the plate. Stress hardness and big relocations are other features of this element. Fluid80 element is also appropriate for calculating hydrostatic pressure and fluid–structure interaction [7].

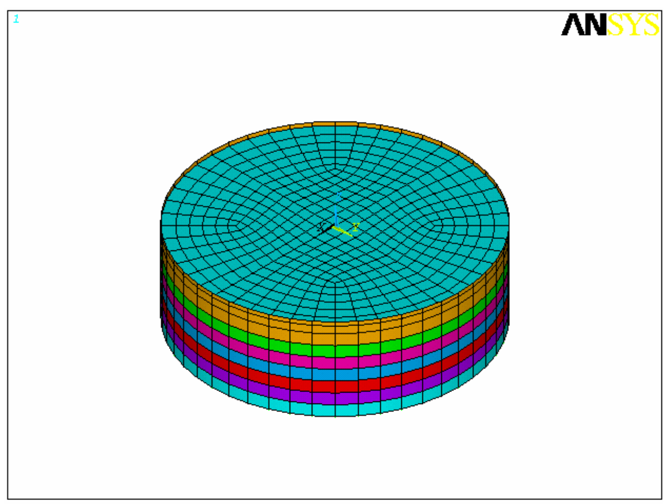

Fig. 1 – 3D model with liquid and how to mesh it

IV. ANALYSIS METHODS

In addition to static analysis, detailed dynamic analysis based on finite element method is necessary for seismic evaluation of studied tanks. In the present study, based on table I, the tanks are classified in five types with height to radius ratio of 0.78, 0.90, 1.0, 1.3 and 2.0 which roughly represent all the tanks commonly used in refineries and industrial complexes. Several analyses including static, modal and linear spectral and nonlinear-time-history analyses have been carried out on the oil storage tank and some results have been obtained. The district seismic risk in which tanks are located has been considered according to the district 3 of Iran Standard 2800 with the maximum acceleration of 0.3 g [8].

TABLE I
PHYSICAL SPECIFICATIONS OF STUDIED TANKS

Type	I	II	III	IV	V
Height(mm)	14640	14640	12810	11920	14640
Diameter(mm)	18595	16250	14235	9170	7320
Height/Radius ratio	0.78	0.90	1.00	1.30	2.00
Floor sheet Thickness(mm)	6.5	6.5	6.5	6.5	6.5
First wall sheet thickness (mm)	18.2	14	9.5	10	8.5
Roof sheet thickness (mm)	5	5	5	4	5
Empty height (mm)	640	640	550	550	640
Roof	float	float	float	fixed	fixed

A. *Static Analysis*

As the first step in qualitative analysis, tanks have been analyzed against their weight and fluid hydrostatic pressure. Besides its impact on loading composition, static analysis could be used as a criterion to evaluate the model. In fact, the hydrostatic pressure creates ring tensile stresses in the wall.

B. *Modal Analysis*

Impulsive parameters of a tank including natural frequencies and model shapes are important factors in the analysis. Determining these parameters in the first step could be very useful in interpretation of tank behavior. In fact, linear modal analysis are used to extract natural frequencies, modal contribution factors and effective mass distribution percentage for each mode. The number of selected modes for dynamic analysis has been selected to include cumulative mass percentages of over 90%. The main frequencies of tank have been compiled including impulsive mode frequency for the fluid vibration and convective mode for the wall vibration that will be used to include analyses [8].

C. *Spectral Analysis*

Once the modal analysis achieved and the main modes determined, we should analyze the tanks spectrally through using the spectrum of site plan. In this analysis, modes have been combined using CQC method and the results of orthogonal directions with 30 and 100 percentages. Based on ASCE instruction, plan spectrum with 10% incident possibility should be used for the next 50 years (return period = 475 yr) for seismic evaluation of refinery facilities. Also the seismic code recommends using 2% attenuation for convective mode and 0.5% for impulsive mode. Figure 2 shows the spectrum of site plan with spectrum of Standard 2800 used in the analysis [3, 6, 8].

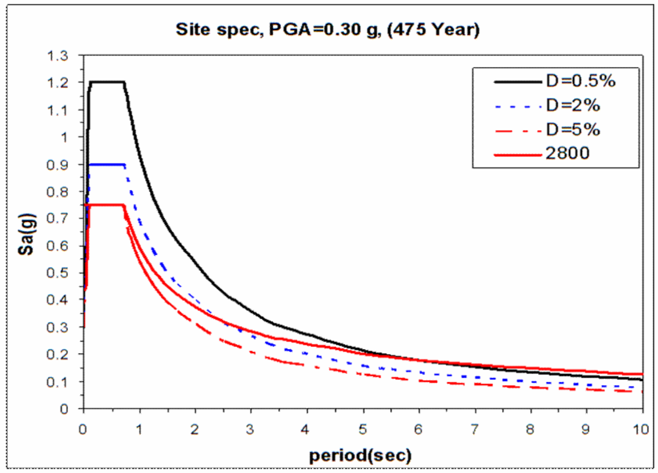

Fig. 2. – Spectrum of site plan for 475-year return period with attenuation of 5%, 2% and 0.5% and Standard 2800

D. *Time History Analysis*

As it said earlier, time history analysis could include all nonlinear factors in the analysis. Therefore, it has been used to estimate the uplifting rate and structure exact responses to this analysis. Time history analysis is aimed to solve the following movement equation for structure floor consequent accelerations.

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=\ddot{u}_g(t)[M] \tag{3}$$

Newmark method is used to solve the equation in time domain. Total attenuation matrix in the equation include attenuation matrices of fluid viscous elements and structure attenuation matrix. For structure attenuation, Riley's attenuation assumption is used, that is, attenuation is linear dependant of mass and hardness. So we have:

$$[C]=\alpha[M]+\beta[K]+\sum_{i=1}^{m}[CF_i] \tag{4}$$

In this equation, [CFi] represents the viscous fluid element, (Fi) the attenuation matrix, and m indicates the number of fluid elements. So α and β coefficients are obtained from the following formula:

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix}=\frac{2\omega_i\ \omega_j}{\omega_j^{\ 2}+\omega_i^{\ 2}}\begin{bmatrix}\omega_j & -\omega_i\\ -1/\omega_j & 1/\omega_i\end{bmatrix}\begin{bmatrix}\xi_i\\ \xi_j\end{bmatrix} \tag{5}$$

In this equation, ωi and ωj represents frequencies of two main modes and ξi and ξj are their related attenuations. The coefficients α and β have been used as input for the time history analysis [3].

In fact, the most important parameters on the earthquake record selection are fault mechanism, conformity of site conditions with record registration station such as layer profile and soil, geology era, station to fault distance, maximum seismic potential of main fault … and since most codes recommend a minimum three records from three different earthquakes, the present study has used earthquake records of Tabas, Golbaf and El-Centro consistent with the site conditions and scaled with maximum acceleration of 0.3g [3, 8].

V. Analysis Results

Here, some results have been discussed from analysis on studied tanks. Note that all units are in Newton, meter and second. Fig 3 shows the hydrostatic pressure distribution of fluid based on statistic analysis. As it was expected the maximum pressure is at the bottom of tank. The frequencies of impulsive and convective modes are also obtained from modal analysis shown in Figure 4 and Figure 5 whose values in tanks type II are 0.1545 Hz and 4.448 Hz, respectively. To obtain the maximum Von Misses stress of tank shell, the loading composition of DL+LL+E/Q has been applied, as the seismic code recommended, and Figure 6 shows the results. In this loading composition; (E) represents 475-year earthquake return and (Q) represents the elasticity-based capacity reduction coefficient [3]. It is seen that the maximum Von misses stress of tank shell for tank type II is 165 MPa.

The maximum fluid height for tank type II, in spectral analysis, is 2.305 m and in time history analysis is 75 cm occurred at second 24 influenced by Tabas earthquake record. Figures 7 and 8 show the results. Figure 9 shows the maximum uplifting floor (24 cm) for tank type V.

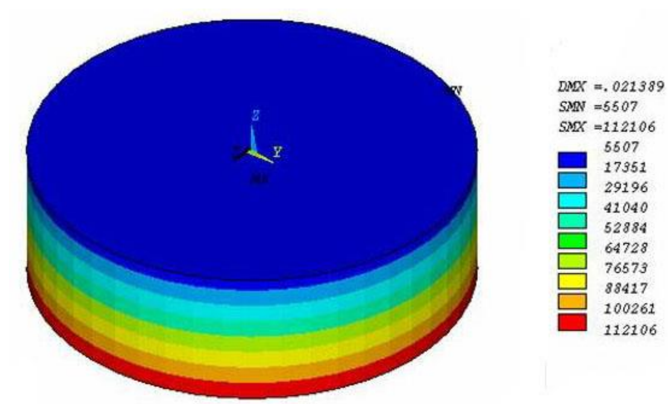

Fig. 3. Hydrostatic pressure distribution of liquid in tank type II

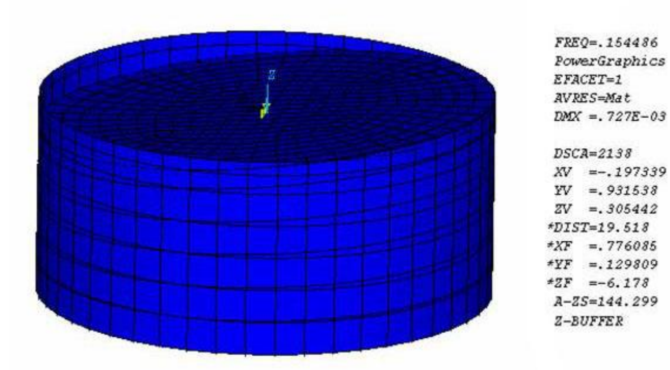

Fig. 4. Frequency of oscillating mode for tank type II (0.1545 Hz)

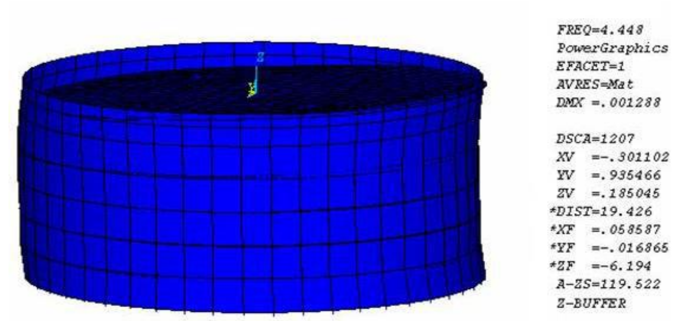

Fig. 5. Frequency of pulsating mode for tanks type II (4,448 Hz)

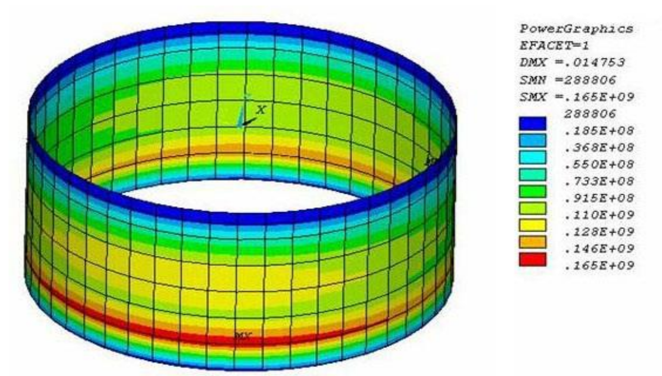

Fig. 6. Von misses stress of wall sheets in tanks type II

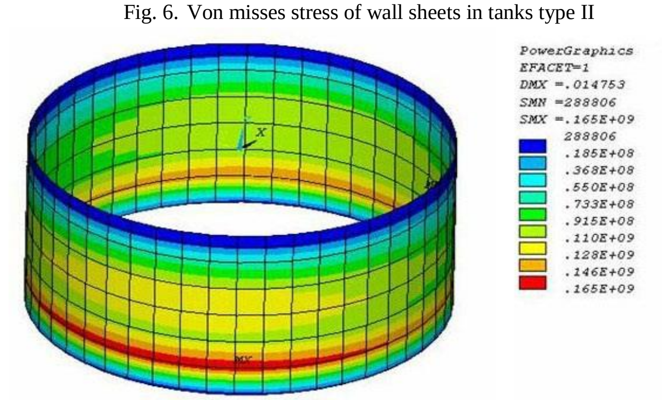

Fig. 6. Von misses stress of wall sheets in tanks type II

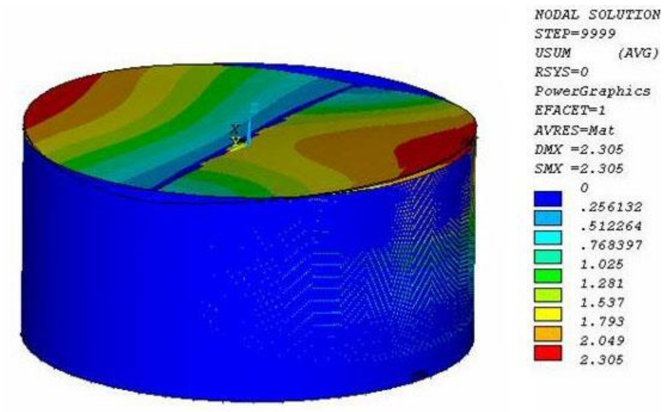

Fig. 7. The maximum fluid height in tanks type II in spectral analysis

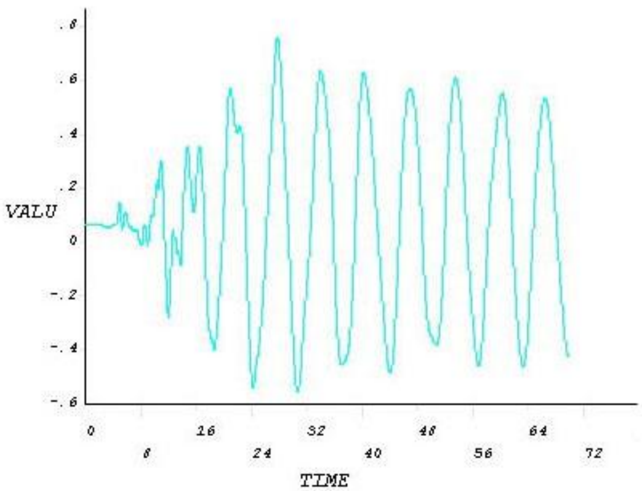

Fig. 8. The maximum fluid height in time history analysis influenced by Tabas earthquake record

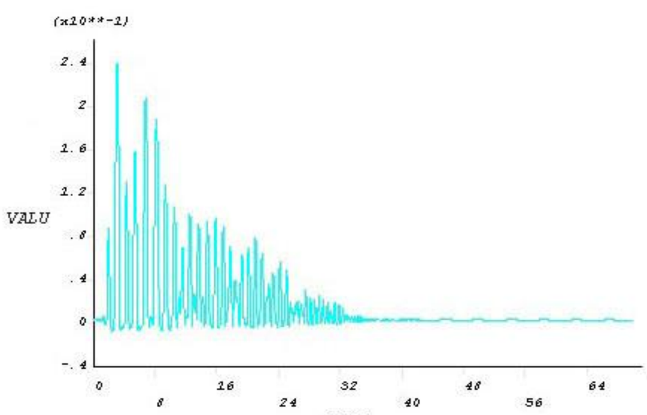

Fig. 9. The maximum floor uplifting for tanks type V influenced by El-Centro earthquake at seconds 6

VI. Evaluating Vulnerability Criteria

Vulnerability of tanks examined in seven criteria and Table II shows the results. The table shows types of tanks, height to radius ratio for each type, frequencies of impulsive and convective modes and the results of seven vulnerability criteria. It is seen that floating roof damage, uplifting floor and consequently asymmetric subsidence and elephant foot buckling have the highest risk factor for tanks during earthquake. In fact, the results reflect the fairly relative status for all tanks which are a warning for infrastructure industries especially oil refineries.

TABLE II
SUMMERY OF VULNERABILITY ANALYSES OF STUDIED TANKS

Type	H/R Ratio	impulsive Mode	convective Mode	Comparison of status quo and the Code	Results of Severn Vulnerability Criteria **						
					1	2	3	4	5	6	7
I	0.78	0.1389	4.110	Available	0.96	172	3.70	23.1	232	1.4	0
				Standard	1.57	226	24.8	45.8	64	30	5
				Safety	+	×	+	×	-	+	+
II	0.90	0.1545	4.448	Available	1.12	165	5.73	15.6	231	2.4	0
				Standard	1.57	226	37.4	31.9	64	30	5
				Safety	×	×	+	×	-	+	+
III	1.00	0.1776	5.018	Available	0.55	159	16.2	8.4	228	19	1
				Standard	1.57	226	32.3	18.5	55	30	5
				Safety	+	×	×	+	-	×	+
IV	1.30	0.2037	4.371	Available	1.17	160	7.69	7.4	172	6.5	0.3
				Standard	1.57	226	39.4	9.7	55	30	5
				Safety	×	×	+	×	-	+	+
V	2.00	0.2358	3.222	Available	1.95	118	*	4.9	158	24	1
				Standard	1.57	226	*	7.1	64	30	5
				Safety	-	×	*	*	-	×	+

* According to the code, it is not necessary to examine diamond buckling for tanks with overturning problem [6].
** 1: Overturning (Dimensionless)- 2: Elephant Foot Buckling (Mpa) – 3: Diamond Buckling (Mpa) – 4: Sliding (MN) – 5: Wave Height (cm) – 6: Uplifting Floor (cm)-

VII. Conclusion

The present study examines seismic behavior of oil storage tanks in five types of tanks with different height to radius ratio and static, linear spectral and nonlinear time-history analyses based on finite element method carried out them. The results show that the frequency of impulsive mode increases as the height to radius ratio is increased and fluid oscillations from vibration of tanks with the current free surface damages the floating roof. In fact, if 18% of tank height is assumed to be empty, fluid turbulences by earthquake will not put the roof at any risk. Also, for unanchored tanks with 1.5 heights to radius ratio and over, overturning will happen and there is no need retrofitting.

As the height to radius ratio increases, there is an increased possibility of diamond elastic buckling to happen in wall and also, elephant-foot buckling has direct relationship with increased diameter of tanks.

The results on unanchored cylindrical oil storage tanks are valid, based on Iran Standard 2800 zoning, located in high seismic risky districts.

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