Performance of Steel Tanks in Chile 2010 and 1985 Earthquakes

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ABSTRACT: A reviewing is done of the main atmospheric vertical steel tank failures occurred in Chile earthquakes of 2010 and 1985 and a comparison with failures occurred in major earthquakes around the world. Tanks performed well during 2010 earthquake due to the use of mechanical anchor of tanks recommended by NCh2369.Of2003 Chilean Standard. Since most of the self-anchoring tanks failed in 1985 Chilean earthquake were designed according to the provisions of API 650-E, it is recommended to review the criteria for the estimate of wall allowable stresses. Mechanical anchoring seems to increase convective stress. High vertical accelerations during subduction Chilean earthquakes make necessary to use mechanical anchoring.

1 INTRODUCTION

Large vertical cylindrical steel tanks supported directly on ground with flat bottom are structures most used to storage a variety of liquid. Seismic design of these tanks in earthquake prone areas is critical due to their importance and sometimes dangerous nature of their contents. Seismic failures of tanks are frequently and the most common form of failure is the called "elephant foot", which occurs on the wall plates of the bottom first course. Despite the large number of research regarding the behavior of these tanks during earthquakes, the design is currently based on the simple hydrodynamic model proposed by Housner (1957) and modified by Veletsos and Yang (1977), which is considered by standards API 650 (2010), AWWA D100 (2006), and the Chilean Standard NCh2369.Of2003 (2003). Despite these design considerations, common failure in storage tanks are repeated in each earthquake, which makes indispensable to revise the proposed theories normally used for the determination of wall stresses. Due to this reason this paper first examines the main types of failure observed in major earthquakes worldwide and second those occurred during the earthquakes in Chile, 1985, M=7.8, and in the 2010, M=8.8 of subduction interplate thrust type. Since tanks in Chile are designed mainly according to API 650 code, following world practice, it is necessary to review and understand the reason of the observed fails in both Chilean earthquakes. One of the most debatable topics among Chilean designers is the need of mechanical anchoring, which well be discussed from the observed tank performance in both earthquakes.

2 OBSERVED TANKS BEHAVIORS DURING LARGE EARTHQUAKES IN THE WORLD

The main type of steel tank failure in world recent earthquakes has been investigated by Pineda (2000), whose results are summarized in Table 1. In this table the most frequently type of failures are identified as:

Rupture of Shell Wall	:	RS
Buckling of Shell Wall (foot of elephant)	:	BS
Failures in Joints Wall – Roof	:	WR
Failures in Columns and Beams	:	CB
Rupture in Roof Plates	:	RP
Rupture of Anchorage Bolts	:	AB
Horizontal Sliding	:	HS

Table 1. Observed tanks failures on earthquakes (Pineda (2000))

Earthquake	Mag.	Principal Failures						
		RS	BS	WR	CB	RP	AB	HS
Chile 1960	9.5		x		x	x		x
Alaska 1964	9.2		x			x	x	x
Armenia 1972	7.0	x	x		x			
Loma Prieta 1989	6.9	x	x	x				x
Hokkaido 1993	7.6		x					x
Northridge 1994	6.7	x	x		x	x	x	x
Observed Failures (%)		50	100	17	50	50	33	83

Despite these tanks were mainly designed according to the criteria of the code API 650 Appendix E, the most common failures are BS (100%) and HS (83%), therefore we recommend to review these criteria for the design of self-anchored tanks. This study will be complemented in this paper by considering the tank performance during the Chilean earthquakes of 1985 and 2010, since Chilean designers also follow API 650 criteria.

3 TANK RESPONSE DURING 1985 CHILE EARTHQUAKE

3.1 *Characteristics of the Chilean Earthquakes*

Central Chile has a high seismicity characterized by the occurrence of large subduction interplate earthquakes with off shore epicenters. This earthquake with epicenter off the city of Algarrobo is the most destructive that has affect this area in the last century, with the exception of the earthquake of Valparaiso in 1906. According to information reported by EERI (1986) occurred two earthquakes on March 3, the first of 5.3 Richter magnitude with epicenter off Algarrobo, with a strong motion duration of 10 seconds and the second, which occurred 10 seconds later of 7.8 magnitude with its epicenter in front of port of San Antonio with a strong motion duration of 30 seconds. Total duration of both earthquakes reached 120 seconds. Records indicate that the earthquake of March 3, 1985, 7.8 magnitude mainly affected the central region of Chile. The maximum recorded PGA was 0.67g in horizontal and 0.81g in vertical directions at Llolleo station near the port of San Antonio (Flores (1993)). Since in Chile the vertical seismic components reach high values, it is necessary to study the need of tank anchoring to reduce the risk of collapse.

3.2 *Performance of Steel Tanks*

Studies of tank damage have been obtained from Flores (1993) and EERI (1986). The damaged tanks were mainly for petroleum storage and were located in the beach of Viña del Mar in the Con Con oil refinery, all damaged tanks were self-anchored with fixed and floating roof. Observed fails in twelve atmospheric tanks were principally elephant foot (BS), only in one case it was detected crack in joint bottom shell with lost of contain. All tanks were self-anchored, and possibly this cause an increment of stress in shell for uplift of wall. Table 2 indicates the main characteristics of tank failures. The later verification of those tanks design according to API 650-88 indicated that they do not satisfy the allowable stresses on shell wall and also the global stability (uplift). Therefore, they must be mechanically anchored and modify their geometry. In the Oxiquim Chemical Plant, located in the northeastern of Viña del Mar (EERI, 1986) 10 storage tanks self-anchored were affected containing chemical products.

Table 2. Tank fails in 1985 Chilean earthquake (Vera (1992))

Tank	H(m)	R(m)	V(m^3)	Product	Roof	Fail
T-326A	12.2	13	1600	Gasoline	Floating	BS
T-326B	12.2	13	1600	Gasoline	Floating	BS
T-418A	12.2	18.3	3200	Nafta	Floating	BS
T-552([1])	12.2	11.2	1200	Solvent	Floating	BS
T-407A	12.2	13.7	1792	Fuel Oil	Conical	BS
T-320A	12.2	11.2	1200	Fuel Oil	Conical	BS
T-4001A	12.2	11.2	1200	Slop	Conical	BS
T-405A	12.2	18.3	3200	Asphalt	Conical	BS
T-420A	11.6	15.9	2285	Kerosene	Conical	([3])
T-301A	9.8	15.2	1760	Kerosene	Conical	([3])
T-422A	12.2	22.4	4800	Kerosene	Conical	([3])
T-402([2])	12.2	22.4	4800	Gasoline	Conical	Without

([1]) Tank more damaged only with break in joint bottom shell, with loss of stored liquid.

([2]) No damage tank.

([3]) Slight deformation.

These tanks have an average capacity of 775m^3 (200.000gal). Failures were observed in welds of the plates of the shell wall; in addition, most of the tanks were filled with fluid and some lost part of its contents. At the Port of San Antonio, close to the station where the maximum horizontal PGA and 0.81g vertical where recorded, there were 26 vertical steel tanks self-anchored, of Terquim, with capacities between 151m^3 (40.000gal) and 1.136m^3 (300.000gal). Tanks had small cracks on the welds joints of the shell wall with roof, so it is important to evaluate the calculation methods for free surface wave height. In conclusion, the earthquake in Chile of 1985, self-anchored tanks presented primarily fails type elephant foot (BS) and horizontal sliding (HS), confirming the results of Pineda (2000) for worldwide earthquake. After this earthquake, in 1986, Chile initiated the study of the NCh2369.Of2003 Standard which differs from API 650 code by the incorporation of mechanical anchoring in tanks, since Chilean earthquakes have significant seismic vertical components, due to uplift or subsidence characteristic of subduction earthquakes. In 1985, most tanks were designed with the API 650 code, since in Chile there was not available an official code for seismic design for steel tanks.

3.3 *Recommendations*

Considering the damage detected in tanks after the earthquake of 1985, Official Chilean Standard (2003) recommended keeping the following considerations for the optimal operation of tanks during their lifetime and prevent failures (Figure 1):

– The roof plates shall not be welded to the purling (Figure 1, details 1 and 2).
– Normal diameter of the air vents on the roof shall be duplicated.

– Piping systems shall be designed with ample deformation capability.
– Leave a freeboard which should be sufficient to reduce the impact of the liquid with the roof.
– In shell plates vertical joints (welds) must not be aligned.
– Generation of design spectra for impulsive and convective modes, considering different levels of seismic hazard.
– The Chilean Standard recommendation of using only one factor R = 4, should be corrected and a different R values for impulsive and convective modes must be used.

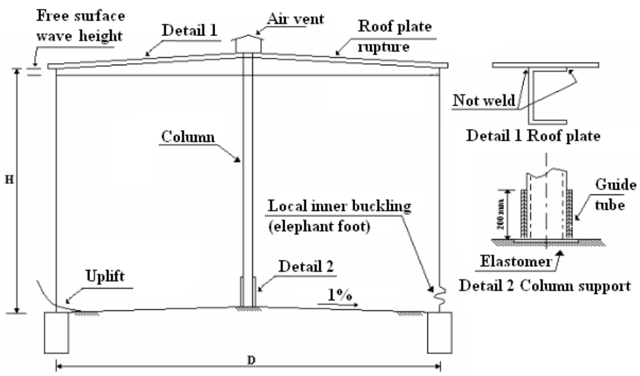

Figure 1. Typical design details of large tanks.

4 OFFICIAL CHILEAN STANDARD NCH2369.OF2003

This Chilean Standard summarized Chilean practice used since the mega earthquake of Valdivia, 1960 (Arze and Vignola (1960)) recommending principally the following criteria:
– The seismic coefficient of the impulsive mode is given in Table 5.7 of code (2003), depending of seismic zone, R factor and ξ, with R=4 and ξ=2% for steel tanks.
– The spectral design acceleration of the convective mode must be determined according to equation (1) considering R=1 and ξ=0.5%; this value in no case shall be less than 0.10 A0/g.

$$C = \frac{2.75A_0}{gR}\left(\frac{T`}{T*}\right)^n\left(\frac{0.05}{\xi}\right)^{0.4} \tag{1}$$

Where, A_0=effective maximum ground acceleration, R=modification factor of the structural response, T`,n=parameters that depends on the soil type, T*=fundamental vibration period in the direction of the seismic analysis, ξ=damping ratio.
This equation is based in the response spectra estimated by Blume (1963) for the 1960 Chilean earthquake of the largest magnitude ever recorded in the world.
– The vertical seismic coefficient shall be equal to 2/3 of the impulsive mode coefficient.
– In mechanically-anchored steel tanks of flat bottom, the design of the anchor bolts shall be carried out such that 1/3 of the number of the bolts are capable of taking the total seismic shear load, unless the anchorage system includes a device that warrants that 100% of the bolts are active to take the seismic shear load. The design of anchor bolts shall consider the simultaneous occurrence of tensile and shear stresses.
– In self-anchored tanks the bottom shall be designed with a minimum conical slope of 1%.
– The Chilean Standard for seismic design recommends the use of the following codes: API 650 -E, AWWA D-100 and NZSSE.

This code recommend to use R=4 in equation (1) for convective mode, which is wrong. Later revision indicates that it must be used R=1. However, this correction has not been done in the code.

5 TANK RESPONSE DURING 2010 CHILE EARTHQUAKE

5.1 *Characteristics of the Chilean Earthquakes*

The 2010 Chilean earthquake occurred 25 years after 1985 earthquake, off the coast of Maule and Biobío Regions on February 27, 2010, with 8.8 magnitude and it is the 6^{th} largest earthquake in magnitude in the world, and the struck area correspond to a part of the affect by 1985 earthquake. This earthquake was recorded by more than 35 accelerographic stations. The maximum PGA was recorded in Angol: 0.93g horizontal and 0.69g vertical (Boroschek et al. (2010)). Cauquenes station was saturated by more than 1g horizontal. Llolleo station similar to the commented 1985 earthquake recorded very large PGA: 0.54g horizontal and 0.70g vertical. Response spectra of Llolleo, Viña del Mar and Melipilla stations were similar to 1985 earthquake. Soil amplification effects were clearly observed in accelerograms. The total duration was more than 2.5 minutes (Saragoni et al. (2010)).

5.2 *Performance of Steel Tanks*

During the 2010 Chilean earthquake there was no observed major fail in tanks, despite the high values recorded of vertical accelerations. This may be due to the recommendation of NCh2369.Of2003 code to mechanical anchor tanks, which apparently increased the convective demand. During this earthquake it were detected few failures of tanks, one of the most important occurred in Santiago's airport. The airport had four fuel steel tanks and one for storing drink water, all of them were of welded steel. The tank containing water collapsed, while the four adjacent tanks of liquid fuels remained intact (Figures 2 and 3). The steel structure of Arturo Merino

Benitez airport had major nonstructural damages, which kept it out of service for a long time. The water tank was self-anchored and had a storage capacity of 1.300m^3 (340.000gal) (Figure 3), which was full at the time of the earthquake. Tank collapse was likely due to repeated wall uplifts and subsequently shells plates buckling.

Figure 2. Collapsed water and nearby liquid fuels tanks.

Figure 3. Collapsed water tank.

Santiago's airport is located in seismic Zone 2 as classified by the Chilean Standard NCh2369.Of2003, a PGA=0.54g horizontal was recorded nearby to Maipu station in similar soil (Pomacita) (Boroschek et al. (2010)). There were no instruments in the area to record this information, but low levels of damage recorded in four fuel tanks (partially filled) and the pumping station, indicated that the local level of ground motion was no larger than PGA=0.25g to 0.35g. The water tank had the following approximate dimensions: diameter 15.24m (50ft), height of overflow level 7.2m (23.5ft), steel wall thickness of lower course 5mm. The calculation of internal hoop stress due to water pressure is about 16.000psi, which is within the typical range for allowable stresses for common design of steel water tanks. The steel tank collapsed rested on a concrete at-grade ring beam. Water pipes were attached to the tank at the lower course and steel roof was supported by steel beams. There was ample evidence of internal corrosion to the steel at and near the roof level, while the front of the tank was painted and did not appear to have much corrosion. The observed failure modes appeared to be tearing of the bottom course from the steel floor plate, with a nearly uniform tear vertically along one of the vertical seam welds in the lower courses (Figure 3). This led to collapse of the tank, with subsequent buckling and tearing of the steel. The uplifted floor plate seen in Figure 3 strongly indicates that tank wall uplift occurred during the earthquake. For self-anchored at-grade steel tanks, this is the expected performance. It is estimated that the force of drain and drag of the stored water were the cause of the fall of masonry walls located near. Tank was located in an area where soil amplification was observed.
Moreover, in the port at Conception Area (San Vicente International Terminal - SVIT), was noted that one tank was tilted approximately one degree, with liquefaction sand boils observed nearest to the roadway portion of this facility. The tank was constructed in 1968, had dimensions of 11.6m diameter and 12m height, and was full during the earthquake. It was not possible to inspect the behavior of liquid fuel tanks near the airport. However, it was detected (from 100m of the tank) minimum failures and it is estimated that were built at the same time that the water tank, using the same paint system and design for the stairs. The types of minor damage to some large storage tanks of liquid fuel from which water tank belong to indicates the possibility that the former had more than 50% full at the time of the quake, it is a common practice. Prior to 2003 it was available a draft of NCh2369.Of2003 code, which was used by many Chilean designers, it allowed verify the performance of tanks designed with this code during the 2010 earthquake. Despite it was been recorded high vertical acceleration during this earthquake no major fails were observed, with the exception of the commented collapse of the airport tank. This may be due to recommended NCh2369.Of2003 code to anchor the tanks, which apparently increase the convective mass demand. Therefore, it is recommended anchor the tanks and study the effect of free surface height wave. Before 2005 tanks were self-anchored, only later dispose of anchors specified in API 650 code version of 2007 (2010) and the Chilean practice NCh2369.Of2003 (2003). This explains the better performance of tanks in 2010 Chilean earthquake.

6 RECOMMENDATIONS

API 650 code was modified later than Chilean 2369.Of2003 code in regard to give recommendation about mechanical anchoring of tanks. Apparently, anchoring generate higher pressure on the roof that require a better estimation of tank freeboard.
Some formulas for calculating freeboard of tanks are the following:

Endesa standard (1987): $\delta = \left(0.10 + 0.25\sqrt{D}\right)(m)$ (2)

Wozniak & Mitchell (1978):

$$\delta = \left(1.124 Z I C_2 T_s^{\,2} \tanh\left(4.77\sqrt{\frac{H}{D}}\right)\right)(ft) \quad (3)$$

NZSEE (1986): $\delta = \left(0.84 R \dfrac{A_1}{g}\right)(m)$ (4)

(Only first sloshing mode)

Where, D=tank diameter in meters or feet, T_s=convective natural period in seconds, Z=seismic zone coefficient, I=essential facilities factor, C_2=lateral earthquake coefficient for convective force, A_1=spectral acceleration for T_s, H=liquid height in meters or feet, R=radius of tank in meters.

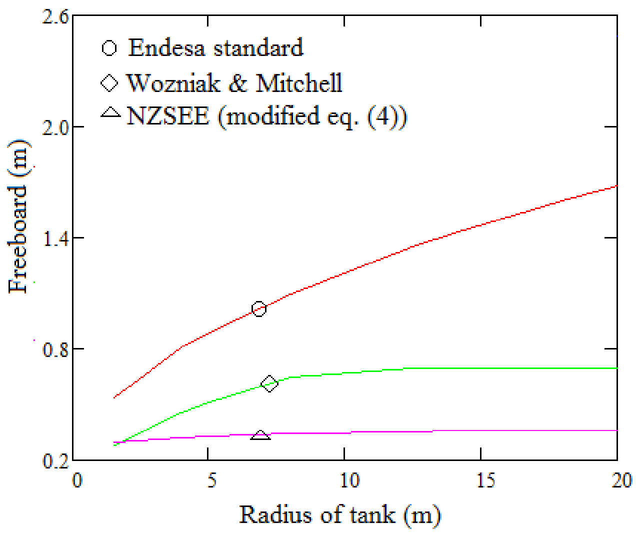

Figure 4. Variation of free surface wave height.

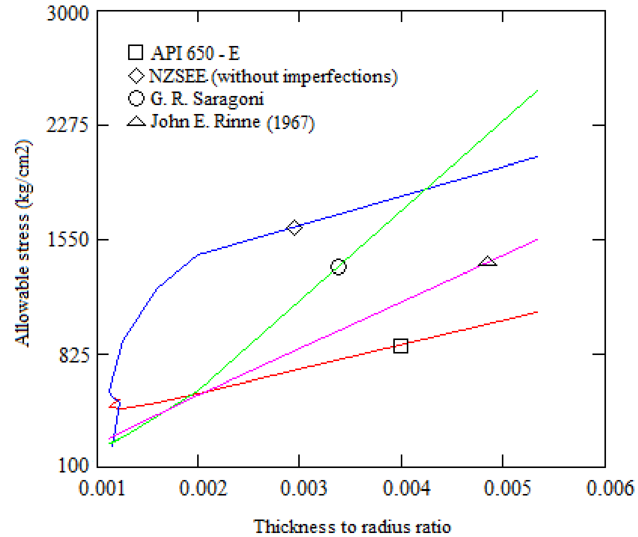

Figure 5. Variation of allowable stress in shell plates.

Figure 4 compares these formulas as function of the tank radius showing important differences that indicates the state of the art in the estimate of the seismic wave height (freeboard). Therefore, it is recommended to investigate the phenomena and calculation methodologies for free surface height wave especially for mechanical anchored tanks. The second recommendation refers to the estimate of the buckling stress on wall steel plate. The buckling stress is defined as:

$$f_{cl} = 0.6E_s \frac{t}{R_s} \tag{5}$$

Where E_s = modulus of elasticity of steel; t = shell thickness, and R_s=tank radius. Clough and Niwa (1979) made a series of experiments on a shaking table to evaluate the seismic response of steel tanks, concluding that its behavior differs from what is observed in real earthquakes. Experimental study of Cambra (1982) demonstrated that the seismic response of tanks was significantly affected by the variation of the foundation flexibility, and a strong correlation was found between tank shell eccentricities, created by fabrication imperfections and/or shell deformations, and the out-of-round response. Figure 5 shows the variations of allowable stress in shell plates tanks for different ratio of thickness/radius, according to the indicated theories. Moreover, considering defects of construction and correct allowable stresses according to the NZSEE (1986), the values are similar to the formula of allowable stress proposed by Saragoni (1994).

7 CONCLUSIONS

The repeated failures occurred in world large earthquakes and in 1985 for self-anchored tanks, such as BS and HS, it's made necessary to review methods used to calculate the shell stresses and consider the possible use of anchors in worldwide of the provisions of NCh2369.Of2003 and API 650 codes, taking into account the good performance of these type of tanks during 2010 Chilean earthquake. The formula for buckling stress for tanks shell (elephant foot (BS)) are noticeable less for API 650 compared with other codes due to imperfection effects which is not included, which may explain the numerous of commented failures. Design trend before the earthquake of 1985 was to self-anchored tanks, it was found that in these cases there is an amplification of stress in the wall, which is higher in tanks with high slenderness. This indicates the importance of tank lifting into the design, therefore it is recommended to do more research in this area.

During the 2010 Chilean earthquake there were no major observed failures in tanks, this maybe due to the recommendations of NCh2369.Of2003 Chilean Standard, to mechanical anchor the tanks. However anchoring apparently increases the convective demand. It's recommended to review the freeboard formulas due to large dispersion.

The Chilean anchoring practice is due to the significant vertical recorded accelerations.

Chilean earthquakes were well recorded, however instrument were no located at tanks site which allow a better estimate of earthquake demand. Instrumentation of tank site is strongly recommended in the future.

8 DEDICATION

Part of this work was conducted with the participation of Professor Elias Arze Loyer in the study by Pineda (2000) on Seismic Design of Large Tanks. The authors dedicate this paper in memory of Professor Arze, who passed away in 2008 before this work was finished.

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