BACKWARD SEISMIC ANALYSIS OF STEEL TANKS

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Abstract. *Steel tanks have presented repeated failures during last large earthquakes, mainly buckling shell, horizontal sliding and some collapse, despite being designed with codes widely used in the world such as the standards API 650-E, AWWA D100, NZSEE and Chilean Standard NCh2369.Of2003. In this study, the backward analysis of the performance of tanks for the following Chilean earthquakes is considered: Central Chile, 1985, Tocopilla, 2007 and Maule, 2010. It is proposed a new formula to estimate the sliding in terms of the magnitude from the backward analysis of these Chilean earthquakes. The sliding in subduction earthquake is in the direction perpendicular to the coast or in the convergence of the subducted plate*.

1 INTRODUCTION

Steel tanks have presented repeated failures during last large earthquakes, mainly buckling shell, horizontal sliding and some collapses cases, despite being designed with codes widely used in the world such as the standards API 650-E, AWWA D100, NZSEE and Chilean Code NCh2369.Of2003. The API-650 E in its introduction recognizes this limited state of the art of seismic design of tanks: "Application of this standard does not imply that damage to the tank and related components will not occur during seismic events". In the work of Pineda and Saragoni (2012), presented in STESSA 2012, studied in detail the behavior of steel tanks in the earthquakes of Chile 2010 and 1985. This paper concluded that the most commonly observed failures in major earthquakes world were buckling shell and horizontal sliding, indicated in Table 1 (Pineda and Saragoni, 2012):

Table 1. Observed tanks failures on earthquakes (Pineda and Arze (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**

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

The first formulas proposed by Housner in 1963 was used to calculate seismic forces on tanks, and then API-650 code incorporated the Housner´s model. This model being simple and is widely used in design codes besides API650-E (petroleum): AWWA (water), NZSEE (any liquid) and the Chilean Code NCh2369.Of2003. In this study, subduction of great magnitudes earthquakes such as the 1960 Valdivia Chile earthquake, the largest magnitude ever recorded in the world with a duration of 5 minutes, and Alaska earthquake in 1964, which lasted 4 minutes, are study.

The work of Douglas Clough (1977) for broad cylindrical tanks is based on results of tanks with slenderness ratios $H / R \leq 1$. The study comes from experimental results using scale models under simulated earthquakes in shaking tables. This work also describes the differences between the observed values and predictive methods. An EERI of University of California, Berkeley group of researchers reviewed the work of Douglas Clough (1977). This work was prepared with the vision of the leading manufacturers of tanks in United States of America; Ray Clough indicates that despite obtained a prediction of axial stresses in the shell based on the amplification of impulsive pressures, no consensus among researchers in considering the observed maximum stresses. In his opinion, it is advisable to conduct investigations into the response mechanisms to better understand the behavior of tanks, before fully accepting any design procedure established.

2 BACKWARD ANALYSIS OF SEISMIC PERFORMANCE OF STEEL TANKS

The backward seismic analysis of steel tanks considers the observed performance of real tanks during large earthquakes, comparing these results with theoretical, experimental or code recommendations in order to understand the commented poor performance of codes. To do backward analysis is required to know the following characteristics of the studied tanks: geometry, anchorage conditions, properties of the liquid, fill heights, seismic ground accelerations and damages (buckling shell and horizontal sliding) and soil foundations.

Rinne (1967) conducted the first backward analysis, with damaged tanks after the mega earthquake of Alaska 1964. In this first backward analysis, not difference between types of earthquakes it was considered. In this work being sorted according to these considerations, since it as will be shown below, most unanchored tanks failed and had large sliding in subduction earthquakes in coast areas. Cooper (1997) develop a backward analysis with information obtained from earthquakes of 1933 to 1995. As it was noted in STESSA 2012, Pineda and Saragoni (2012) concluded that in most earthquakes considered the common damage observed was buckling type "elephant foot" and horizontal sliding (Figure 1).

One of the important limitations to apply the backward analysis is that de most industrial facilities with seismic failed tanks farm do not recognize publically their problem due to commercial, insurance or prestige reasons. In this paper, we have extended the backward analysis conducted by Cooper (1997) incorporating information from the results shown by Pineda and Saragoni (2012), summarized in Table 2.

Other paper on backward analysis of failed oil tanks during the subduction Tohoku, Japan 2011 earthquake is due to Zama et al. (2012), they reported three types of main failure: first due to tsunami, second due to long period ground motions and third due to short period strong ground motions that produced soil liquefaction failure. In addition, two big fires occurred at oil refineries were reported.

The backward analysis will be extended in the next section of this paper considering the following three Chile subduction earthquakes: Central Chile, 1985, Tocopilla, 2007 and Maule, 2010.

Table 2. Earthquakes characteristics, soils foundations and tanks properties in major earthquakes.

Earthquake	Mag.	Mech. of Faulting	Distance to Fault[2]	Epicentre Distance	Failure	Soil Type[1]	Fluid Level (earthquake)
Long Beach 1933	6.4	Cortical	2-5km	3.5-45km	BS/AB/RS	N/I[1]	Full
Kern County 1952	7.5	Cortical	N/I[1]	3.2-42km	BS	Alluvial	Full
Chile 1960	9.5	Subduction	N/I[1]	N/I[1]	BS	Sand[5]	N/I[1]
Alaska 1964	9.2	Subduction	N/I[1]	130km	BS/HS	Silt-Clay	Full
San Fernando 1971	6.7	Cortical	N/I[1]	21km	AB/BS	N/I[1]	(1/2-2/3)H
Armenia 1972	7.0	Cortical	N/I[1]	N/I[1]	BS	N/I[1]	N/I[1]
Imperial Valley 1979	6.5	Cortical	4-5km	30km	RS	Rock	Full
Coalinga 1983	6.7	Cortical	N/I[1]	6.5km	BS	N/I[1]	3/4H
Loma Prieta 1989	6.9	Cortical	N/I[1]	40km	RS	Alluvium	Full
Landers 1992	7.3	Cortical	100km	N/I[1]	BS/HS[4]	N/I[1]	N/I[1]
Hokkaido 1993	7.6	Subduction	N/I[1]	80km	BS	Poor	N/I[1]
Northridge 1994	6.7	Cortical	Near	8km	BS	Rock	Full
Kobe 1995	6.9	Cortical	2-4km	10km	Tilting	(3)	N/I[1]

(1) N/I: no information available
(2) Tectonic Plates
(3) Liquefaction
(4) Horizontal sliding: 80mm
(5) Compacted sand filling

3 PERFORMANCE OF STORAGE TANKS DURING CHILE SUBDUCTION EARTHQUAKES

In this paper, the following Chilean earthquakes of great magnitude are study: Central Chile, 1985, Tocopilla, 2007 and Maule, 2010.

All these studied earthquakes are subduction interplate type characterized by large coseismic displacement of some meters measured by GPS in the coast area and large horizontal and vertical acceleration with durations of minutes, which affect the seismic performance of tanks. Most of the studied tanks are located in coastal zone, therefore affected by the mentioned characteristic of these subduction earthquakes, which are study in detail. The studied subduction earthquakes are characterize to deliver high levels of seismic energy at few asperities on the subducted plate. Because of the similarity in construction and seismic response between oil, water and others liquids tanks, the conclusions and recommendations obtain in this work can use for these types, including variations related to the seismological characteristics of the earthquake and site foundation. When the tank suffers structural damages but does not lose its contents, the tank is consider to have functioned satisfactorily, in the Chilean code NCh2369.Of20003; this is call design criteria of continuity of operation by the industry. In the next sections, the backward analysis is detail for each of the studied Chilean earthquakes.

3.1 Central Chile 1985

The earthquake on March 3, 1985 had its epicentre in the city of Algarrobo and was of magnitude 7.8 on the Richter scale, accelerations were recorded 0.67g horizontal and 0.81g vertical, with a duration of 95 seconds. In ENAP Refinery located in the city of Con Con, there was a series of eleven tanks in which they were observed buckling type "elephant foot" which is indicated in Table 3, generating strain at the bottom of the first ring of the shell and no sliding of these tanks was observe. The tanks were left out of service for repairs and unanchored only placed on improved landfill.

Table 3. Observed tanks failures on Enap Refinery (Vera (1992)).

Tank	R (m)	H (m)	H_1 (m)	H_2 (m)	Product	Fail
T-326A	6.48	12.2	11.30	10.61	Gasoline	BS
T-326B	6.48	12.2	11.30	11.20	Gasoline	BS
T-418A	9.14	12.2	11.30	11.23	Nafta	BS
T-552 (1)	5.59	12.2	11.80	11.56	Solvent	BS
T-407A	6.86	12.2	11.60	11.56	Fuel Oil	BS
T-320A	5.59	12.2	11.60	10.42	Fuel Oil	BS
T-4001A	5.59	12.2	11.60	11.15	Slop	BS
T-405A	9.14	12.2	11.60	11.33	Asphalt	BS
T-420A	7.92	11.58	11.60	1.94	Kerosene	(2)
T-301A	7.62	9.75	9.20	3.26	Kerosene	(2)
T-422A	11.17	12.2	11.60	7.88	Kerosene	(2)
T-402	11.20	12.2	11.30	10.80	Gasoline	(3)

H_1: Maximum height of the liquid (sloshing).
H_2: Filling height at March 3, 1985.
(1) Tank more damaged only with break in joint bottom shell, with loss of stored liquid.
(2): Slight deformation.
(3): Undamaged.

The corresponding two asperities of this subduction earthquake are shown in Figure 2. The asperity, close Valparaiso, Con Con, where ENAP Refinery is located shown horizontal displacement of the plate of more than 2.0 meters.

3.2 Tocopilla Earthquake 2007

The Tocopilla earthquake occurred on November 14, 2007 was of magnitude 7.7. Near the epicentre area is located the tank TK-201 Interacid owned company located in Mejillones plant. In this plant, there are two steel tanks with similar characteristics, being one empty and one with liquid, information that was provide after the earthquake. The damaged tank is unanchored according to the requirements of API650-E. This tank has a diameter of 35m, height 14.5m and shell thicknesses varying between 8mm and 25mm. At the time of the earthquake, it was partially fill with acid with specific gravity 1.83ton/m^3, reaching a liquid level of about 9.1m at the time of the earthquake, with a freeboard of 314cm. The maximum horizontal accelerations recorded on the ground of 0.42g and 0.41g in Mejillones and Tocopilla. The maximum vertical accelerations recorded on ground of 0.36g and 0.27g in Mejillones and Tocopilla city. Under the foundations of the tanks are bad graduate burdensome sandy soils and sands with few fines. Tank TK-201 presented effect of earthquake damage such as buckling type “elephant foot” at the top of the shell and lifting of the base with permanent deformation of 70 to 80mm. Horizontal sliding was observed from 80 to 100mm in the perpendicular direction to the coast and corresponding to the convergence direction of the subducted Nazca plate (Figure 3). The bottom plate of the tank was wrinkled by the horizontal displacement. In Figure 4 are shown two plate asperities due to Tocopilla 2007 earthquake ((Peyrat et al. (2009)) showing displacement larger than 1.5 meters in Tocopilla zone, similar to 1985 Central Chile earthquake. The tank TK-201 was located at the south asperity near Mejillones, suffering horizontal displacement, which in larger magnitude earthquake could be about 1 meter.

3.3 El Maule Earthquake 2010

The earthquake of February 27, 2010 occurred in the Maule was a mega earthquake of magnitude 8.8 on the Richter scale with its epicentre area near ENAP Bio Bio Refinery located in the city of Talcahuano in the coast area built in 1960, which had a major expansion in 1990. Most tanks at the refinery were built in 1990, its construction predates the publication of the Chilean standard NCh2369.Of2003, and therefore tanks were designed with the requirements of API650-E code for seismic zone 4. The soil in the area of tanks farm is sand of dense medium consistency with upper layers of loose material. In areas with farm tanks, damage by lateral spreading and soil liquefaction it was observe.

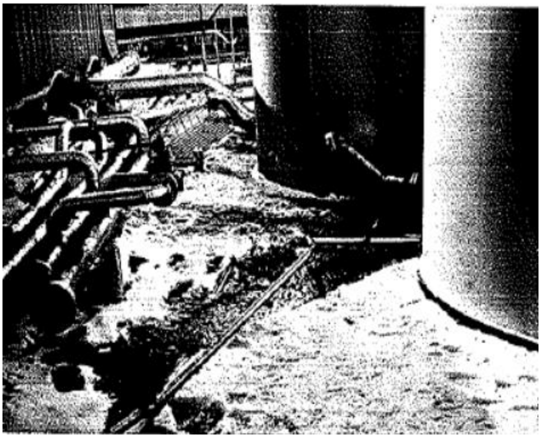

Figure 1. Horizontal sliding tank of 1524mm. 1964 Alaska earthquake. Rinne (1967).

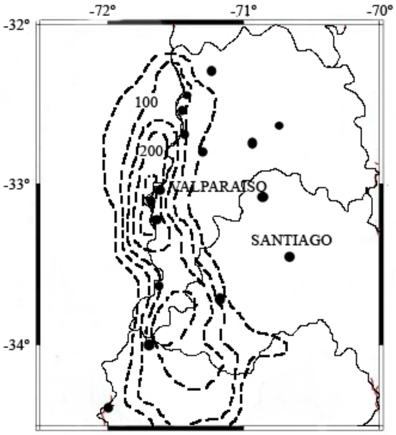

Figure 2. Central Chile 1985 earthquake. At least two large zones of asperities (modified from Barrientos (1988)).

Figure 3. Horizontal sliding (80mm) Tank TK-201. 2007 Tocopilla earthquake.

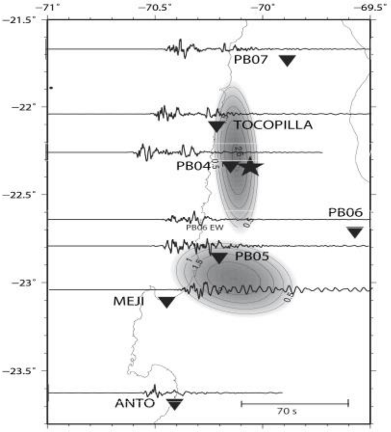

Figure 4. North Chile Tocopilla 2007 earthquake. At least two large zones of asperities. South asperity at Mejillones location of the TK-201 tank (Peyrat et al. (2009)).

At the time of construction of tanks, the design criteria of the current version of API650 were consistent with the Uniform Building Code 1991. The tanks have the ring system reinforced concrete foundation without anchors connected to the tank shell. After the earthquake of 2010 minor damage were detected specifically in three floating roof tanks. The earthquake was recorded by more than 35 accelerograph stations, the maximum PGA was recorded in Angol city, with the following values: 0.93g horizontal and 0.69g vertical. The recorded peak acceleration in downtown Concepción near ENAP Refinery was 0.40g horizontal and 0.36g vertical. (Boroschek et. al. (2010))

Figure 5. Tank T-6020 with spilled oil. El Maule earthquake 2010.

Figure 6. Tank T-6030. With tilt due to liquefaction soil lateral spreading. 2010 El Maule earthquake.

At the time of the earthquake were two tanks filling height leaving low freeboard, so the "crude oil" spilled in about 270 ° around the perimeter of these tanks. One of the floating roof was not damaged and the other had some damage on the pontoons. There were no fire tanks. Figure 5 show the T-6020 tank having 67m in diameter by 14.6m height, floating roof designed with the provisions of API650-E with seismic zone 4 and importance factor 1.0. At the time of the earthquake the tank was filled with a height of 13.7m, the convective period was approximately 11seg, which considerably exceeds the range of periods spectra recorded for 2010. Using quake recorded value of PGA = 0.4 g, the provisions of API605-E and a range of convective periods of 4 to 8sec, values tidal wave of 1.0 to 2.1m is obtained approximately. Figure 6 shows the tank T-6030 of 67m in diameter and 14.63m of high, with floating roof, built in 1995 according to the provisions of API650-E eighth edition, considering seismic zone 4 and coefficient of importance 1. This tank present a (lateral spreading) settlement 54mm due to the soil liquefaction. The earthquake struck the tank with a capacity of 25 percent full fluid. Despite the above, bottom plates are deformed due to settling for soil liquefaction. This effect caused the rupture of the fillet welds on the bottom plates.

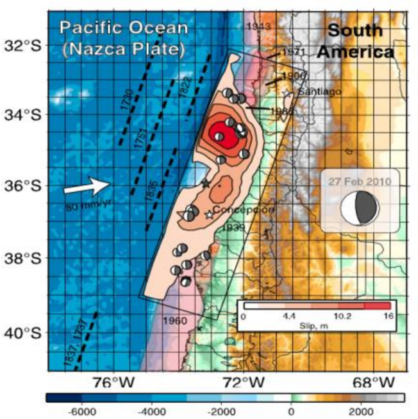

Figure 7. Asperities of El Maule 2010, Chile M=8.8 earthquake. South asperity near Concepcion indicate sliding of 10 meters. (Lay et al. (2010)).

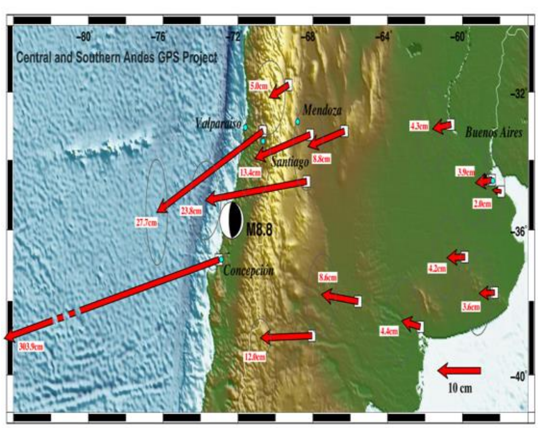

Figure 8. GPS coseismic horizontal displacement after 2010 El Maule earthquake showing 303.9 centimetres at the coast of Concepción, where ENAP Refinery was located. (https://www.soest.hawaii.edu/soest_web/soest.news_chile_feb2010_eq.htm.)

This case is very interesting since despite foundation soil was improved, seismic liquefaction was developed, similar the observed behaviour in Tohoku 2011 earthquake (Zama et al. 2012). In this earthquake, slip phenomenon was not observed due to liquefaction that ground functioned as "seismic isolator". In Figure 7 shown the two main asperities of the El Maule, Chile 2010 earthquake. The sliding of the south asperity near Concepción where ENAP Refinery is located was about 10 meters. Figure 8 shown the GPS horizontal coseismic displacement after the earthquake of 303.9 centimeters in Concepción where ENAP Refinery was located. This large horizontal coseismic no vibratory displacement of the coast are characteristic of the subduction mega earthquakes, which with the simultaneous large vertical acceleration can induce large horizontal tanks displacements such the 1.524 meters indicated by Rinne (1967) for Alaska mega earthquake shown in Figure 1.

4 SEISMIC HORIZONTAL SLIDING OF SELF ANCHORED STEEL TANKS

In previous sections has been noticed that one of more common seismic failures of tanks is horizontal sliding. These sliding are assumed generally due to inertial pressure forces on the tanks, however according the backward analysis of tanks located in coastal areas of subduction large earthquakes; the sliding can be due to the coseismic displacement of meters of the coast measured by GPS. Table 3 summarizes the observed slide of tanks.

Table 4. Principal observed horizontal tanks sliding.

Earthquake	Magnitude	Plate Fault	Horizontal Sliding (mm)	D(m)	H(m)
Alaska	9.2	Subduction	1524	3.2	9.144
Tocopilla	7.7	Subduction	80	35	14.5
Landers	7.3	Cortical	70-80	16.5	7.3

From Table 3 can be appreciated that sliding of tanks can reach values of meters in coast areas of subduction earthquakes. The following preliminary formula to estimate the sliding S of tanks in coastal areas of subduction zones in terms of magnitude M is proposed:

$$S[m] = -5.47 + 0.76M \quad ; \quad M \geq 7.3 \tag{1}$$

The sliding in subduction earthquake is in the direction perpendicular to the coast or in the convergence of the subducted plate. Considering this formula, anchors of tanks will be required in some cases despite API 650-E recommendation in order to avoid damage in bottom plates as well as piping. The sliding also produce seismic forces not consider in API650-E and other design codes for unanchored tanks. It must keep in mind that the small sliding have produced failure in bottom plates.

5 CONCLUSION AND ACKNOWLEDGMENTS

From the backward analysis of tanks located in coastal areas of three large Chilean subduction interplate earthquakes the horizontal sliding was estimate. The main conclusion is that large sliding are due to large ground displacement of meters measured by GPS in coastal areas. A formula is propose to estimate the sliding in terms of the magnitude indicating that in some cases despite API 650-E recommendations anchored will be needed for unanchored tanks to avoid failures of bottom plates and piping. The sliding in subduction earthquake is almost static in the direction perpendicular to the coast or in the convergence of the subducted plate.

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