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ANALYSIS OF STEEL TANKS IN CHILE SUBDUCTION EARTHQUAKES

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Abstract

Steel tanks have presented repeated failures during last large earthquakes, mainly buckling of shell, horizontal sliding and some collapses, despite being designed with codes widely used in the world such as the standards API 650-E, AWWA D100, NZSEE and Chilean NCh2369.Of2003, causing significant losses in the production of heavy industry, especially for burning generation after the earthquake. This unwanted performance was confirmed again to analyze a large number of tanks located in epicentral subduction zones of Chile, most of these cases studied were designed with the code API 650-E, confirming that it is necessary to modify the design codes to limit frequent failures, since there is no consistency with the observed, despite permanent evolution of design codes. The high seismicity of Chile as well as the large magnitude of their recent subduction earthquakes has allowed to measure instrumentally new effects on the design of steel tanks that may contribute to observed failures. In this study, the backward analysis of the performance of tanks for the following Chilean earthquakes is considered: Central Chile, 1985, Tocopilla, 2007, Maule 2010 and Illapel 2015. In the Chilean Earthquakes Maule 2010 and Illapel 2015, important coseismic horizontal GPS displacements were measure at the coast, showing that is the characteristic of the interplate subduction large earthquakes. This horizontal displacement may produce horizontal sliding of tanks in the direction perpendicular to the coast on the convergence of the subducted plate. To avoid horizontal sliding of the tanks due to these coseismic displacements of the self-anchored solution for the tanks is proposed. Anchored tanks during the Chilean earthquakes showed good performances. In the most recent Illapel earthquake Mw=8.4 of September 26, 2015, the network of wide band accelerograph measured important displacement in the relative displacement spectrum in the range of 10 to 15 sec. Since the sloshing period of tanks is in this period range, the effects on the different sloshing formulas is analyzed. The characteristics of the soils foundation are also considered, since determine seismic response of steel tanks. Finally, the review of anchored and self-anchored cylindrical tanks and main fails after these large earthquakes, which were located in epicenter subduction zones near of Nazca plate asperities, with available design information to perform "Backward Seismic Analysis" is considered.

Keywords: Tanks; Anchored; Backward; Subduction; Coseismic.

1. Introduction

Chile is one of the most seismically active countries in the world, for this reason and considering that it has a significant number of processing plants where flat steel tanks on the ground are very important for production processes, both conditions make possible to develop the Backward Analysis methodology based on the observation of the behavior of these tanks in large Chilean earthquakes to assess their seismic response. The pioneers in the development of backward analysis studies for steel tanks were Rinne [1] during the great Alaska 1964 earthquake and Cooper [2], who made a compilation of tank response data in major earthquakes recorded between 1933 and 1995. Both published the necessary information related to the characteristics of tanks and observed damage, but was Rinne who proposed a method for estimating seismic coefficients and allowable stresses in shell. Tanks performed well during 2010 Chile earthquake due to the use of mechanical anchor of tanks recommended by NCh2369.Of2003 Chilean Standard [3]. Since most of the self-anchoring tanks failed in 1985 Chilean earthquake were designed according to the provisions of API 650-E [4], it is recommended to review the criteria for the estimate of wall allowable stresses, as well as codes AWWA D100 [5] and NZSEE [6] because they use similar methods for seismic analysis, having variations in design methods. The API-650 Standard (Annex E), It recognizes that its design recommendations do not limit the seismic damage of tanks: "Application of this standard does not imply that damage to the tank and related components will not occur during seismic events". Since mechanical anchoring seems to increase impulsive and convective stresses, considering the high vertical accelerations during subduction Chilean earthquakes it is recommended to use mechanical anchoring. After the 2010 Chile earthquake there was great interest in countries like the United States on behavior of industrial structures in Chile according to an assessment by Soules in ASCE report of 2016 [7], because it is the only country that has prepared a separated code of seismic design especially for heavy industrial plants originated from a study Backward Analysis to maintain the continuity of operation by the industry [8]. In recent conferences of STESSA [9, 10] Backward Analysis studies developed by Pineda and Saragoni have been presented which confirmed the need for such studies to generate better design procedures for the benefit of mitigating tank damage during earthquakes.

2. Develop of Backward Analysis for 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 (shaking table) in order to understand and improve the codes provisions that despite their use damages in the tanks are repeated. To do backward analysis is required to know the following characteristics of the studied tanks: dimensions and shell thicknesses, design criteria and codes used, as built drawings, foundations and anchorage systems, properties of soils, types of liquid contents, fill levels during earthquake, seismicity and ground accelerations and damages (Table 1). It is important to note that the origin of failure of tanks designed with the codes based on the theoretical model develop by Housner [11], which in addition to experimental tests (shaking tables) do not reflect the real behavior of tanks during earthquakes, because their assumptions are not complied, such as: effect thin wall, liquid behavior (similarity laws), imperfections in plates shell reduce allowable stress, soil mechanics studies, earthquake directivity. EERC studies [12, 13, 14, 15] conclude that most used standards: API-650 and AWWA-D100 sub estimate real shell stress. Also it is evident the different views between academics, researchers and manufacturers. These studies were funded by manufacturer companies of steel tanks. In general owners do not provide information of damage to tanks after earthquakes and implement systems of instrumentation due to burning risk for contain flammable liquids, this implies shortage of relevant information to assess the seismic response on tanks during earthquakes. The first formulas proposed by Housner in 1963 [16] was used to calculate seismic forces on tanks, and then Standards API-650, AWWA D100 and NZSEE incorporated the Housner´s model. This model being simple, but has some limitations such as: not considered imperfections of shell plates, inertial forces when the self-anchored tanks slides horizontally and effect of anchors systems.

3. Characteristics of Subductions Earthquakes in Chile

The studied Chilean subduction earthquakes are of interplate type. They are generated between Nazca and Southamerican plate in few zones of contact know as asperities of the plate. The asperities of the main Chilean earthquakes are shown for Central Chile 1985 (Figure 1), Tocopilla 2007 (Figure 2) and El Maule 2010 (Figure 3). The continuous sliding of the oceanic Nazca Plate of 6cm/year is restrained by few protuberances of the plate or asperities, which release the seismic energy when stresses at the asperities exceeds their capacity. Due to this effect of the asperities the Southamerican plate suffers shortening due to the compression which is released in few seconds as a coseismic one directional displacement perpendicular to the coast mainly at asperity locations (Figure 9). The coseismic displacements are measured by GPS [17], that in the case of El Maule 2010 earthquake indicated 3.0m in direction perpendicular to the coast at Concepcion City shown by the main arrow in Figure 4. This coseismic sliding of subduction earthquakes of meters is almost static and occurs in almost a minute in large earthquakes. Most of studied tanks of industrial facilities are located in coast zones, therefore the effect of subduction interplate earthquakes is studied in detail and the effect of coseismic displacement in particular.

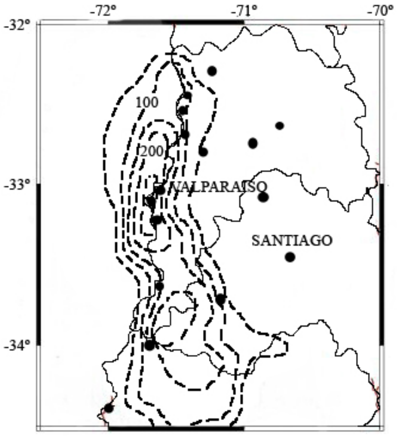

Figure 1. Central Chile 1985 earthquake. At least two large zones of asperities (modified from Barrientos (1988)) [18].

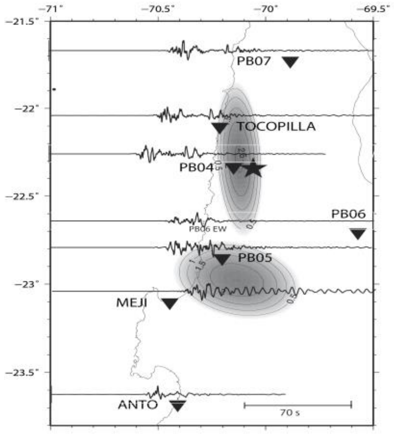

Figure 2. Tocopilla 2007, Chile earthquake, two asperities identified in northern Chile near of Mejillones city [19].

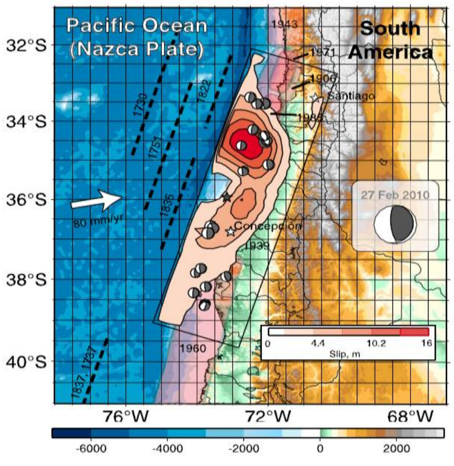

Figure 3. Asperities of El Maule 2010, Chile earthquake. Asperity near Concepción with sliding of 10 meters [20].

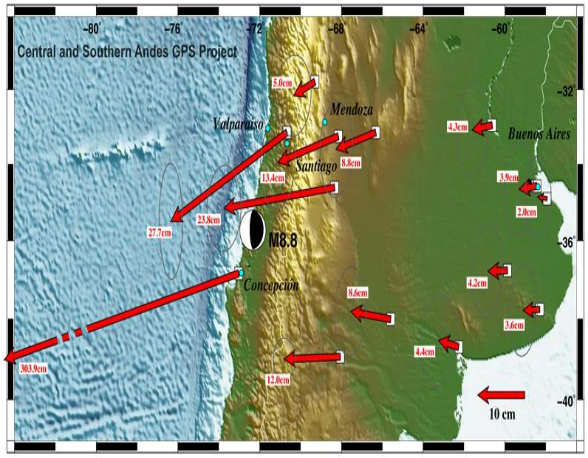

Figure 4. GPS coseismic horizontal displacement after 2010 El Maule earthquake showing 303.9 centimeters at the coast of Concepción, close to ENAP Refinery. [https://www.soest.hawaii.edu/soest_web/soest.news_chile_feb2010_eq.htm].

In Figure 2 are shown the mainly plate asperities by effect of Tocopilla 2007 earthquake showing displacement larger than 0.8 meters in Tocopilla (sulfuric acid plant) zone, similar to 1985 Central Chile earthquake. One tank was located at the south asperity near Mejillones, suffering horizontal displacement, which in larger magnitude earthquake could be about 1 meter.

4. Behavior of Steel Tanks in Large Chile Earthquakes

In this paper the main failures in tanks are identified, despite having been designed by codes widely used in the world [4, 5, 6]. The results were obtained after analysis of major earthquakes in Chile on coastlines exposed to tsunami, such as Chile 1960, 1985, 2007 and 2010. Analysis of large number of tanks located in epicentral subduction zones of Chile confirmed that it is necessary to modify the design codes to limit frequent failures, since there is no consistency with the observed performance despite the permanent evolution of design codes. Central Chile has a high seismicity characterized by the occurrence of large subduction interplate earthquakes with offshore epicenters and tsunamis. It has been prepared an important collection of data necessary for generating a backward analysis, this mainly through publications obtained for 1985 Chile earthquake from Flores [21] and EERI [22], project documents, publications of 1964 Alaska earthquake [1, 23] and a work developed by Cooper [2] for major earthquakes in the world. In 1985 Chile earthquake the main damaged tanks were for petroleum storage and were located in the coast of “Viña del Mar” city in the ENAP Con Con Oil refinery, all damaged tanks were self-anchored with fixed and floating roof (Table 1) and the main fail was buckling of shell type “elephant foot” (Figure 5). The 2007 Tocopilla earthquake was of magnitude 7.7. Near the epicentre area is located the tank of sulfuric acid plant located in Mejillones city. Two steel tanks with similar characteristics were revised, being one empty and one with liquid, information that was provide after the earthquake. The damaged tank is self-anchored 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 a freeboard of 314cm. The observed tank presented effect of earthquake damage such as buckling of shell type “elephant foot” (Figure 6) nearly of the half height of shell and lifting of the base with permanent deformation of 70 to 80mm. During the 2010 Chilean earthquake there was no observed major fails in tanks, despite the high values recorded of vertical accelerations. This may be due to the recommendations of Chilean code NCh2369.Of2003 to use mechanical anchor on tanks, which apparently increased the impulsive and convective demands. There are four large liquid fuels and one water tank located at one site the Santiago International Airport, all welded steel. The tank site is located in Chile "seismic zone 2", which translates to a seismic design level motion of $A_0 = 0.30g$. During this earthquake it were detected one collapsed tank (Figure 7) while the adjacent four liquid fuels tanks remained intact. The water tank had a storage capacity of 1.300m3, which was full at the time of the earthquake. Tank was self-anchored, lower course of wall thickness are 5mm (less than required by design codes) and water pipes were attached rigidly at the lower course of shell plates (Figure 8). The uplifted floor plate seen in Figure 8 strongly indicates that tank wall repeated uplifts and subsequently buckling of shells plates, which can be the reason of collapse. This is the expected performance in this case. Moreover, the undamaged fuel tanks were designed and built with anchors bolts, lower course of wall thicknesses of 8mm, which is within specified by the design codes and explains the good behavior during the earthquake. The tanks analyzed (Figure 10) located near of epicenter of 2010 El Maule earthquake, corresponding to ENAP Bio Bio Refinery [7] and was built in 1990s. Since the mounting of these tanks it has been done before of publication of Chilean Code NCh2369.Of2003, most of tanks was designed with requirements of standard API 650 Appendix E. Tanks was supported by concrete rings walls and they are self-anchored. Three external single deck pontoon floating roof tanks experienced some problems. No elephant foot buckling was noted. Earthquake slosh produced liquid spilling. The identification of pulses propagated from asperities [17] that control the rupture of these earthquakes is an important problem for seismic analysis since it can reduce the failures and sliding in tanks. A number of studies of large Chilean earthquakes have revealed that the source time functions of these earthquakes are composed of a number of distinct energy arrivals. Two well recorded interplate earthquakes, the 1985 Central Chile (Ms = 7.8) and the 2007 Tocopilla (Mw = 7.7), are considered. A good recognition of dominant asperities in seismic zones can reduce overestimates due to scattering of attenuation formulas that consider epicenter distance or shortest distance to the fault rather than the asperity distance.

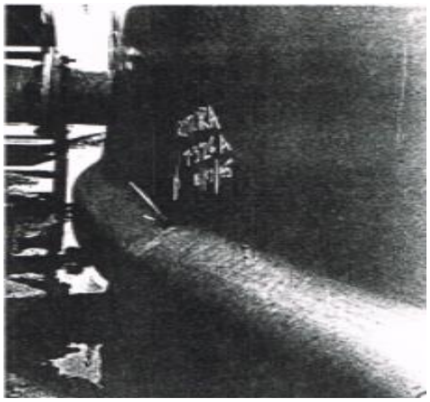

Figure 5. Algarrobo, Chile 1985 earthquake, buckling shell, Oil refinery. Buckling of Shell foot elephant.

Figure 6. Tocopilla, Chile 2007 earthquake, sulfuric acid plant. Buckling of shell.

Figure 7. El Maule 2010, Chile earthquake. Collapsed water tank nearby liquid fuels tanks, Santiago Airport.

Figure 8. El Maule 2010, Chile earthquake. Large deformations of water pipes connected to shell tank, Santiago Airport.

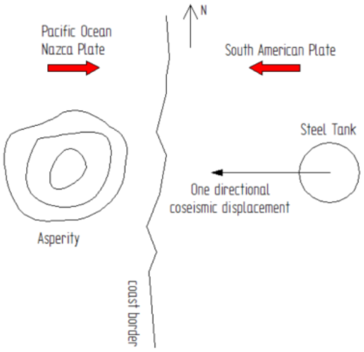

Figure 9. Effects of asperities in tanks in coast subduction zones.

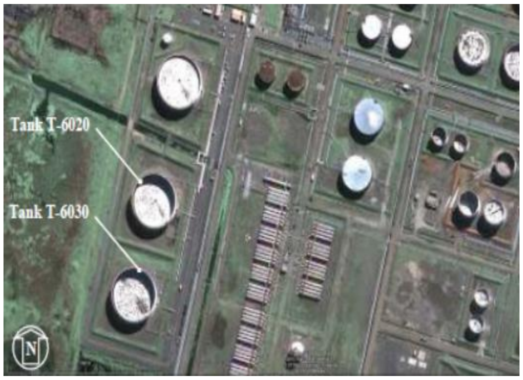

Figure 10. El Maule 2010, Chile earthquake, view of western area at ENAP Bio Bio Oil refinery.

Table 1 – Cases Studies of Tanks in Large Earthquakes in Subduction Zones

Earthquake	Location	Mag.	Quantity	Content	Failure
Chile 1985	Algarrobo	7.9	12	G, N, So, Fo, Sp, A, K	BSL, U
Chile 2007	Tocopilla	7.7	1	Sa	BSU, HS
Chile 2010	El Maule	8.8	7	Sa, W, MT, G, D, T	U, CL,
Alaska 1964	Anchorage	9.2	24	W, O, Tf,	CL, RD, CB, BSL, BSU, U, BL, HS
Alaska 1964	Nikiski	9.2	7	W	CL, BSL, RD, U
Alaska 1964	Seward	9.2	1	Fo	BSL, B

Content: (G)Gasoline, (N)Nafta, (So)Solvent, (Fo)Fuel Oil, (Sp)Slop, (A)Asphalt, (K)Kerosene, (Sa)Sulfuric acid, (W)Water, (MT)Metil ter butyl eter, (D)Diesel, (T)Tar (alquitran), (O)Oil, (Tf)Turbine Fuel

Failure: (BSL)Buckling Shell Lower (type “elephant foot”), (U)Undamaged, (BSU)Buckling Shell Upper, (HS)Horizontal Sliding, (CL)Collapse, (RD)Roof Damages, (CB)Columns and Beams damages, (BL)Bottom Lift, (B)Burning.

5. Results of Backward Analysis

In this section the results of Backward Analysis for steel tanks are studied for interplate subduction large earthquakes (Chile 1985, 2007 and 2010), the observed failures and expected seismic responses in earthquakes are analyzed.

5.1 Tanks Designed According to API650 with Observed Failures

We reviewed a set of tanks designed with standard API650-E 8th edition [24], which were operating at the time of the 1985 Chile earthquake with more than 93% of content for their full capacity, according to records of the refinery. The 1985 Chile earthquake was characterized by significant ground accelerations, especially verticals component of 0.81g, which conditions the use of anchors in the tanks to reduce convective effect and risk of lifting of shell, thus increasing tensions of compression. This is reflected in the observed damage during the earthquake that relate to buckling of shell type "elephant foot" mostly as shown in Table 2. The tanks were out of service due to repairs. The shell compression (σ_{sc}) calculated for self-anchored tanks, were considerably less than the allowable shell compression (F_{asc}) between 13 and 20% of the allowable value, see Figure 11. However, it was detected more than two thirds of the tank shell buckled (Table 2), which is evidence of underestimates of the allowable stresses by code for tanks located in areas near the asperities as shown in Figure 5. Since these tanks were exposed to a greater amount of energy not considered in seismic design codes, as explained above. All these tanks require the use of anchors, but they were self-anchored. The failures indicated in Table 2 and horizontal sliding can be eliminated with the incorporation of anchorage. Since the similarity in construction and seismic response between oil, water and others liquids tanks, the conclusions and recommendations of these analyzes can use for all these types, taking in consideration the variations of the seismological characteristics of earthquakes and site foundations. When the tanks have structural damage, but can be repaired and not lose its contents, it is considered to function satisfactorily. In the Chilean code NCh2369.Of20003, this is called design criteria by continuity of operation of the industry.

Table 2 – Observed tanks failures on 1985 Chile earthquake

Tank	**D/ H_1**	**H_1**	**H_2**	**R_c (%)**	**Failure**
T-326A	1.06	12.20	11.30	94.4	BSL
T-326B	1.06	12.20	11.30	92.6	BSL
T-418A	1.50	12.20	11.30	92.6	BSL
T-552 (1)	0.92	12.20	11.80	92.6	BSL
T-407A	1.12	12.20	11.60	92.6	BSL
T-320A	0.92	12.20	11.60	95.1	BSL
T-4001A	0.92	12.20	11.60	100	BSL
T-405A	1.50	12.20	11.60	95.1	BSL
T-420A	1.37	11.58	11.60	95.1	(2)
T-301A	1.56	9.75	9.20	95.1	(2)
T-422A	1.83	12.20	11.60	96.7	(2)
T-402	1.84	12.20	11.30	95.1	(3)

D: Diameter (m)

H_1: Shell height (m)

H_2: Filling height (m) at March 3, 1985 earthquake

R_c: Shell Compression / Allowable Shell Compression

BSL: Buckling Shell Lower (type “elephant foot”)

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

(2): Slight shell deformation

(3): Undamaged

5.2 New Results Obtained from Backward Analysis Not Considered in Design Codes

Of 51 tanks analyzed located in areas of subductive interplate earthquakes: Chile 1985, 2007 and 2010, plus Alaska 1964, the Figure 12 shows the important differences for estimate the wave height /freeboard according to usual methods in Chile practice, therefore, it is recommended to investigate this phenomena and calculation methodologies especially for mechanical anchored tanks. Considering the fill heights of these tanks for 1985 Chile earthquake, the vibration periods for the convective mode are between 2 and 9 seconds (Figure 13), being special attention over 7 seconds since according to the displacement spectra of 2010 Chile earthquake, values greater than 20 cm were reached (Figure 14).

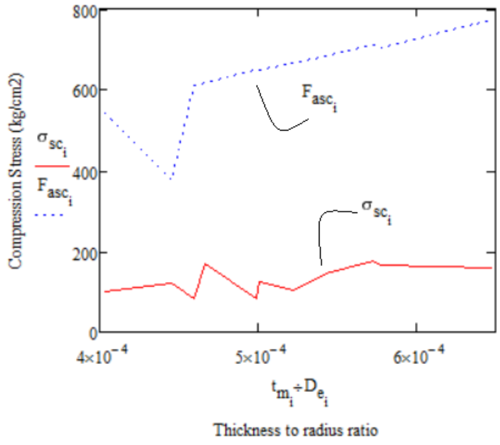

Figure 11. Tank performance in 1985 Chile earthquake for shell compression, showing that allowable stress is 13 to 20% of estimated shell compression despite the observed buckling of shell. σ_{sc} (calculated), F_{asc} (allowable), both in kg/cm^2.

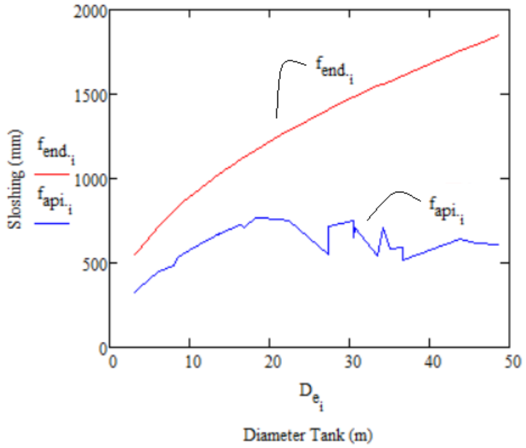

Figure 12. Sloshing wave calculated according to some codes used in the Chilean practice. f_{end} (Endesa standard), f_{api} (API650 Appendix E), both in mm.

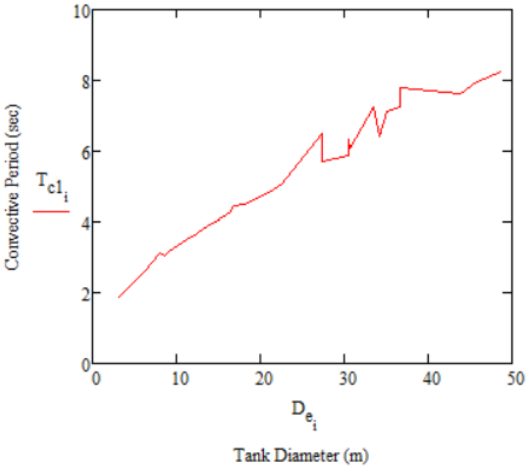

Figure 13. Convective Periods for studied tanks, 1985 Chile Earthquake. T_{c1}: convective period calculated for studied tanks, in seconds.

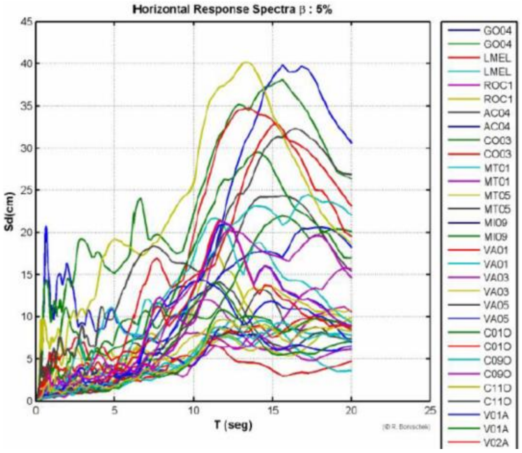

Figure 14. Horizontal displacement response spectra, subductive interplate Chile earthquake, 2015 Illapel (M_w=8.4). Boroschek [25].

5.3 Coseismic Effects on Anchored and Self Anchored Tanks

This is necessary to develop studies Backward Analysis; as usual design codes do not consider the destructive effects on structures effects of different types of mechanisms of tectonics plates. One of more common seismic failures of tanks is horizontal sliding are assumed generally due to inertial pressure forces on the tanks. According to backward analysis of tanks located in coastal areas of interplate subduction large earthquakes; the sliding can be due to the coseismic displacement of meters of the coast measured by GPS (Figure 4). The sliding in subduction earthquake is in the direction perpendicular to the coast or in the direction of convergence of the subducted plate. This one direction sliding occurs in 30 or 40 secs having a quasistatic characteristic producing inertial forces mainly in the opposite direction. This one directional force is not considered by the code since it superposes to the vibratory forces due to vibration of the ground measured by the acceleration response spectra.

The following preliminary formula to estimate the coseismic horizontal sliding "S" of tanks in coastal areas of subduction zones in terms of magnitude M has been proposed by the authors [10]:

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

It should be noted that displacement registers shown by displacement spectra in Figure 14 refer to vibratory motions, whereas the formula (1) and the sloshing of Figure 16 shows an inertial behavior in the mentioned coseismic direction. 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, in addition to reducing the risk of buckling of shell. 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 has produced failure in bottom plates. Table 3 indicate sliding (S) of tanks in coast areas of subduction earthquakes. In 2007 Tocopilla Chile earthquake, the tank located on acid plant in Mejillones city, was detected a horizontal sliding between 80 to 100mm in the perpendicular direction of the coast and corresponding to convergence direction of subducted Nazca plate. According to the orientation the tank indicated in Figure 15 in perpendicular direction to the coastline besides the buckling of shell showing in Figure 6, explains the influence of the earthquake directivity. For the 2010 Chile earthquake Figure 10 shows that the tanks are oriented in direction N-S, on the other hand, Figure 16 shows that the central tank had slosh in W-E direction perpendicular to the coastline, similar to the above mentioned case for the earthquake 2007, confirming the influence of the coseismic directivity of the subductive Chilean earthquake. This effect is incident on the seismic response of tanks with a predominant the convective mass. In both cases the tanks were self-anchored, so it is important to consider a possible horizontal sliding in future earthquakes for tanks located in subductive zones near of asperities and assess the application of the equation (1). Figure 17 shows some tanks located in a gas plant in San Vicente port, tank on the west side on Figure 18 had an inclination of a one-degree perpendicular to the coastline, confirming once again that Chilean coast earthquakes dominated the directivity in the direction of subduction. The tank was built in 1968, it had height dimensions of 11.6m in diameter and 12 meters, and was full during the 2010 Chile earthquake.

Table 3 – Horizontal sliding (S) observed in earthquakes.

Earthquake	**Magnitude**	**Plate Fault**	**S (mm)**
Alaska 1964	9.2	Subduction	1524
Tocopilla 2007	7.7	Subduction	70-80
Landers 1992	7.3	Cortical	80-100

Figure 15. Tocopilla, Chile 2007 earthquake, sulfuric acid plant. Failure in the earthquake directivity.

Figure 16. El Maule, Chile 2010 earthquake, ENAP Bio Bio Refinery. Earthquake directivity.

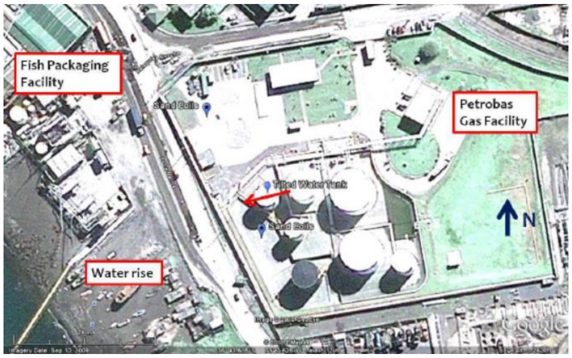

Figure 17. Plan view of the San Vicente Port gas facility, 2010 Chile earthquake, red arrow indicates the earthquake directivity.

Figure 18. Tilted water tank at gas facility in the 2010 Chile earthquake.

6. Recommendations

It is important to have design methods to ensure the good performance of the tanks during major earthquakes, or at least prevent its collapse, since the damage caused by leakage or fires generate large economic losses in money, environmental destruction and loss of life, whose effects can last several days and it is the typical fire failure due to interplate subductive earthquake. Figure 19 shows fire at Valdez, Alaska for 1964 subductive earthquake. The tank fire was triggered by failure of others oil storage tanks at the Union Oil tank farm. Buildings along Front Street and Standard Oil's pumping control station also fire. The Union Oil tank farm was burn for two weeks. Figure 20 shows a refinery that was burnt out completely by the fires, located in a petrochemical complex in Sendai area. There was a gasoline tank, asphalt tanks, molten sulfur tanks and oil handling. The welded part of the gasoline tank between the shell plate and the bottom plate fractured along approximately 2.4m. Can be inferred from both the on-site investigation and the interview to working staffs that the floating oil spill ignited due to the spark at the collision between tank lorries and oil handling facilities by the tsunami. Is recommended use anchor systems (according to Chilean Code NCh2369) considering high vertical accelerations components (Chile), good performance has been observed after large earthquakes.

Figure 19. Burned tank five hours after the 1964 Alaska earthquake with a large fire across the coastline [26].

Figure 20. Burned-out zone refinery, 2011 Japan Earthquake [27].

7. Conclusions

Some of the described tank performance can be only estimated by backward analysis as coseismic displacement which can nor reproduced by shaking table.

In major Chilean Earthquakes important coseismic horizontal GPS displacements were always measured at the coast, indicating this is a characteristic of the interplate subduction large earthquakes. This horizontal displacement may produce horizontal sliding of tanks in the direction perpendicular to the coast, due to this and to avoid horizontal sliding of self-anchored tanks, solution for the tanks is proposed, considering that most of analyzed tanks of industrial facilities are located at coast zones in subduction areas.

According to results of Backward Analysis (Figure 11), the allowable stresses calculated by the API650-E standard used in the design of tanks observed in the Chile earthquake of 1985 are considerably lower that stresses of shell compressions, which results in an underestimation of the requirements of this standard design.

Mechanical anchoring increase impulsive and convective stresses and considering the high vertical accelerations during subduction Chilean earthquakes it is recommended to use mechanical anchoring, according to recommendations of Chilean code NCh2369.Of2003.

8. Acknowledgements

Is highly recognized the cooperation of Bio Bio ENAP Refinery, “Compañía de Acero del Pacífico (CAP)” and senior structural engineer Sergio Contreras.

9. References

[1] Rinne, E. (1967): Oil Storage Tanks, in volume II-A: The Prince William Sound, Alaska, earthquake of 1964 and aftershocks. Environmental Science Services Administration. U.S. Coast and Geodetic Survey. Washington: Government Printing Office. P. 245-252.

[2] Cooper, T. W. (1997): A Study of the Performance of Petroleum Storage Tanks During Earthquakes, 1933-1995. United States Department of Commerce Technology Administration. National Institute of Standards and Technology, NIST. June.

[3] Official Chilean Standard NCh2369.Of2003: “Earthquake-resistant design of industrial structures and facilities”, National Institute of Normalization (in Spanish).

[4] API Standard 650 (2013): “Welded Tanks for Oil Storage”, Twelfth Edition, March 2013, Addendum 1 September 2014, Errata 1 July 2013, Errata 2 December 2014, American Petroleum Institute.

[5] ANSI/AWWA D100 (2011): “Welded Carbon Steel Tanks for Water Storage”, American Water Works Association, AWWA Standard, July 1.

[6] New Zealand Society for Earthquake Engineering (2009): “Seismic Design of Storage Tanks: 2009”, Recommendations of a NZSEE Study Group on Seismic Design of Storage Tanks.

[7] Soules, J. G., Bachman, R. E., Silva, J. F. (2016): “Chile Earthquake of 2010, Assessment of Industrial Facilities around Concepción”. ASCE, Structural Engineering Institute.

[8] Blume, J. A. (1963): A Structural-Dynamic Analysis of Steel Plant Structures Subjected to the May 1960 Chilean Earthquakes. Bulletin of the Seismological Society of America. Vol. 53, No. 2, pp. 439-480.

[9] Pineda P., Saragoni G. R. and Arze L. E. (2012): “Performance of Steel Tanks in Chile 2010 and 1985 Earthquakes”. Proceedings of the 7th International Conference on Behaviour of Steel Structures in Seismic Areas - STESSA, Santiago, Chile, pp. 337-342, February 9-11.

[10] Pineda P. and G. R. Saragoni (2015): “Backward Seismic Analysis”. Proceedings of the 8th International Conference on Behaviour of Steel Structures in Seismic Areas - STESSA, Shanghai, China, pp. 337-342, July 1-3.

[11] Housner, G. W. (1954): Earthquake Pressures on Fluid Containers, California Institute of Technology. Eighth Technical Report under Office of Naval Research.

[12] Clough, R. W. & Niwa, A. (1979): Static Tilt Tests of a Tall Cylindrical Liquid Storage Tank. Earthquake Engineering Research Center. Report NO. UCB/EERC-79/06 February 1979.

[13] Clough, D. P. (1977): Experimental Evaluation of Seismic Design Methods for Broad Cylindrical Tanks. Earthquake Engineering Research Center. Report No. UCB/EERC-77/10.

[14] Manos, G. C. and Clough, R. W. (1982): Further Study of the Earthquake Response of a Broad Cylindrical Liquid-Storage Tank Model. Earthquake Engineering Research Center. Report NO. UCB/EERC-82.

[15] Lau, D. T. and Clough, R. W. (1989): Static Tilt Behavior of Unanchored Cylindrical Tanks. Earthquake Engineering Research Center. Report NO. UCB/EERC-89/11. College of Engineering, University of California – Berkeley, California.

[16] Housner, G. (1963): "The dynamic behaviour of water tank", Bulletin of the Seismological Society of America, vol. 53(2), 381-87.

[17] Ruiz, S., Madariaga, R., Astroza, M., Saragoni, G. R., Lancieri, M., Vigny, Ch. and Campos, J. (2012): Short-Period Rupture Process of the 2010 M_w 8.8 Maule Earthquake in Chile. Earthquake Spectra. The Professional Journal of the Earthquake Engineering Research Institute.

[18] Barrientos S, (1988): "Slip distribution of the 1985 Central Chile earthquake", Tectonophysics, 145, 225-241.

[19] Peyrat S, Madariaga R, Buforn R, Campos J, Asch G, Vilotte J P (2009): "Kinematic Rupture process of the 2007 Tocopilla earthquake and its main aftershocks from teleseismic and strong-motion data", Geophysical Journal International.

[20] Lay T., Ammon C. J., Kanamori H., Koper K. D., Sufri O., Hutko A. R. (2010): Teleseismic inversion for rupture process of the 27 February 2010 Chile (Mw 8.8) earthquake, Geophysical Research Letters, 37, L13301, doi:10.1029/2010GL043379.

[21] Flores, R. (Editor) (1993): Case of the Chile Earthquake of March 3, 1985, Hachette, July, Santiago, Chile (In Spanish).

[22] EERI, The Chile Earthquake of March 3, 1985 (1986): Earthquake Spectra, The Professional Journal of the Earthquake Engineering Research Institute, Volume 2, Number 2.

[23] Hanson, R. D. (1973): Behavior of Liquid-Storage Tanks: The Great Alaska Earthquake of 1964. Committee on the Alaska Earthquake of the Division of Earth Sciences National Research Council. P. 331-339.

[24] API Standard 650 (1988): "Welded Steel Tanks for Oil Storage", Eighth Edition, November 1988, American Petroleum Institute.

[25] Boroschek, R. (2015): Preliminary Report Strong Motion Records Analysis. University of Chile.

[26] National Centers for Environmental Information (2016): March 28 of 1964 Prince William Sound USA earthquake and tsunami.

[27] Zama S., Nishi H., Hatayama K., Yamada M., Yoshihara H., Ogawa Y. 2012. "On Damage of Oil Storage Tanks due to the 2011 off the Pacific Coast of Tohoku Earthquake (Mw9.0), Japan", 15th World Conference on Earthquake Engineering, Lisboa – Portugal.