TANK DESIGN RECOMMENDATIONS FOR SEISMIC CODES ON CRITICAL INDUSTRIAL FACILITIES

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Abstract

Large atmospheric steel storage tanks are widely used in petrochemical and process plants in the world. It has been observed that, during major earthquakes: Chile (1960, 1985, 2007 and 2010), Alaska 1964, United States (1933-1995) and Japan 2011, areas with great industrial and oil activity, the seismic tank behavior has been poor despite being designed with the standards API 650-E, AWWA-D100 and NZSEE, presenting repeated failures. In addition, the API 650-E code recognizes its limitations indicating that its use does not imply that no damage occurs during seismic event, despite it is also currently used for the design of most tanks located in critical installations. Experimental tests and theoretical models do not reflect the real structural responses during major earthquakes, since there is no correlation between the code recommendations and observed damages. In this work, result obtained from seismic backward analysis of past earthquakes is provided with information collected from subduction and cortical earthquakes. In particular, the information provided by Pineda & Saragoni (Chile, 1960-2010), Rinne (Alaska, 1964) and Cooper (United States, 1933-1995) which includes records of seismic characteristics and responses during major earthquakes are considered in the backward seismic analysis of this work. Some of the analyzed tanks are in critical facilities such as oil and industrial plants, ports, airports and hospitals. In previous works Pineda & Saragoni (STESSA 2012 and 2015, 16WCEE, ACHISINA 2019) have presented studies of seismic backward analysis based on the Chilean high seismicity, which confirm the need to include modifications to the most used standards to improve the seismic response of tank. These studies have confirmed the presence and effects of seismic directivity, considerable dispersion on calculation of sloshing wave and underestimation of stresses in shell, which explain the observed poor structural behavior of tanks during large earthquakes. Recent measurements of dynamical GPS coseismic horizontal displacement in one direction of 304 centimeters in 40 seconds at the coast for 2010 Chile earthquake, shows that this duration is like broad tanks sloshing period, therefore in this work the recommended formulas of sloshing wave are improved to include this new effect. Recommendations for the calculation of sloshing wave, design spectra (R and ξ), shell stresses, horizontal sliding, use of anchors bolts and seismic classifier factor for risk limits in designs are given. In large Chilean earthquakes, the influence of coseismic directivity in the direction of subduction in coastal zones has been observed, similarly effects will be studied in major United States earthquakes. In this work, design recommendations are suggested to reduce observed damage in tanks.

Keywords: Tanks, Anchored, Backward, Subduction, Coseismic

1. Introduction

This paper presents the method of Backward Seismic Analysis (BSA) for steel tanks using information obtained from 245 tanks in operation during major subductive earthquakes: Valdivia 1960, Chile Central 1985, Tocopilla 2007, El Maule 2010, in addition to Alaska (1964) and others occurred in the United States between 1933 and 1995 (subductive and cortical), being the only work available with this categorization and results that define the origin of the damage and mitigation measures. Part of these tank (140) records are included in table 1 of this work. Information on areas with high seismic activity and industrial process plant records where steel tanks are relevant in production have been incorporated, both aspects are necessary for the development of the BSA method based on the observation of the seismic behavior of steel tanks. It has been observed that most tanks without anchors have failed during large earthquakes and were designed primarily with the code API 650-E [1], which indicates in its annex E that its seismic design methodology has limitations in its recommendations design, noting: "The application of this standard does not imply that during seismic events damage to the tanks and their components occur." Given the above, it is necessary to review and modify the design criteria for the calculation of the permissible stresses in shell, together with the recommendations of the AWWA-D100 [2] and NZSEE [3] codes because they contain similar procedures to estimate the seismic solicitations, but with different design methods. The tanks require special treatment in the analyzes, especially when they are filled with liquid, since their behavior is different from other traditional structures subjected to seismic forces. This is because the vibrating frequencies of the shell-liquid system are in very distant ranges, with high periods (convective or sloshing mode) that can exceed 10 seconds in large diameter tanks and periods less than 1 second in the confined liquid in the lower area of the tank. Generally, the structures designed with seismic codes rarely show failures in major earthquakes, however in the tanks repeated failures have been observed in different countries of the world. Therefore, for the conferences of STESSA 2012 [4], STESSA 2015 [5], 16WCEE [6] and the work of thesis Master in Seismic Engineering of the author [7], the causes of the failures were investigated concluding that mainly because the tanks designed with API 650-E were not anchored, in addition the design codes do not consider relevant aspects that condition the seismic response.

2. Characteristics of Subductive Earthquakes in BSA Studies

In this work, the behavior of steel tanks during interplate subductive earthquakes was analyzed, which are generated by the continuous sliding of about 6cm/year between the Nazca and South American oceanic plates, restricted in the contact areas known as asperities of the plates, which release a large amount of seismic energy when exceeded in their capacities. The asperities of the main Chilean earthquakes have been located in the central zone in Algarrobo 1985 (Figure 1), Tocopilla 2007 (Figure 2) and El Maule 2010 (Figure 3). During the El Maule earthquake (Figure 4), 3m coseismic displacements were measured with GPS perpendicular to the coast of the Concepción city. The characteristic non-vibratory horizontal displacements of 6cm for mega earthquakes, together with the high vertical accelerations of the soil, can induce large horizontal displacements in the tanks, such as the cases recorded in Tables 1 and 2. The displacement between tectonic plates has generated horizontal sliding of the tanks in the direction perpendicular to the coast in the direction of the convergence of the subducted continental plate, this is explained in section 3.5 of this work on the effects of seismic directivity and sliding of the non-anchored tanks can be estimated with Equation (1) of this work. To avoid horizontal sliding of the tanks, the use of anchoring systems in tanks is recommended, in accordance with the provisions of standard NCh2369 [11].

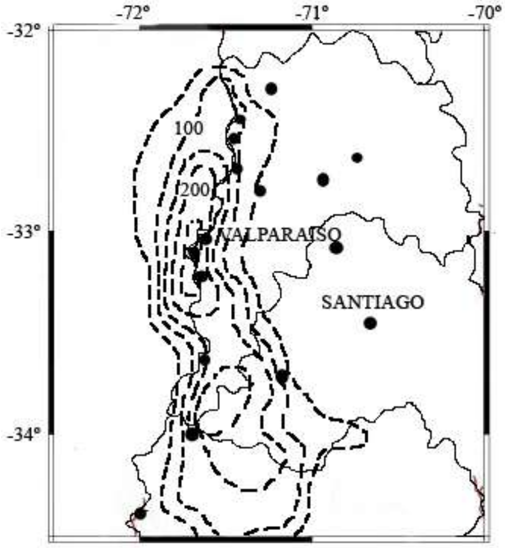

Fig. 1 – Chile Central 1985 earthquake, central zone. Records of two large areas with asperities edges (modified by Barrientos [8]).

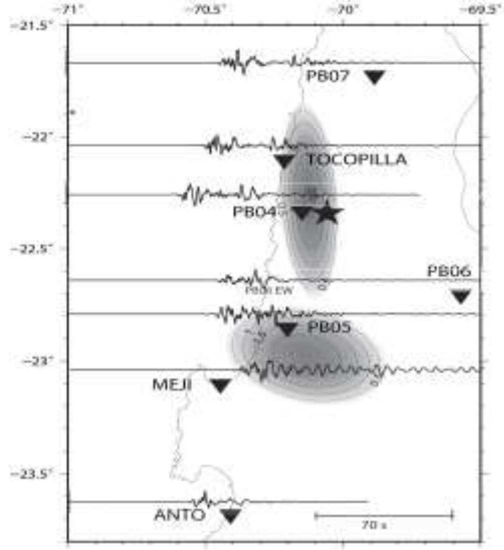

Fig. 2 Tocopilla 2007 earthquake. Two asperities edges were identified near the city of Mejillones (Peyrat et al. [9])

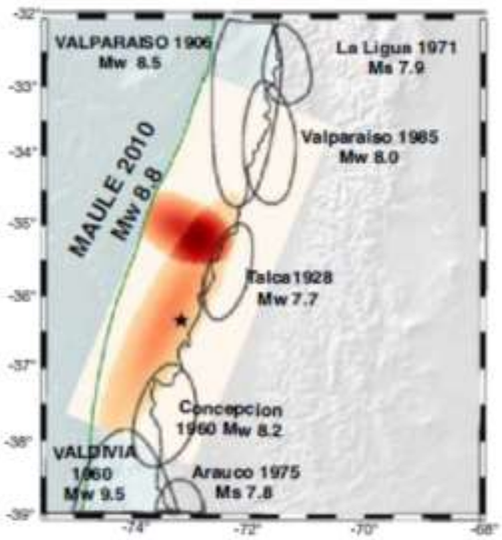

Fig. 3 – El Maule 2010 earthquake. Asperities located near the cities of Concepción and Constitución with 10m tectonic plate sliding (Lay et al.) [10].

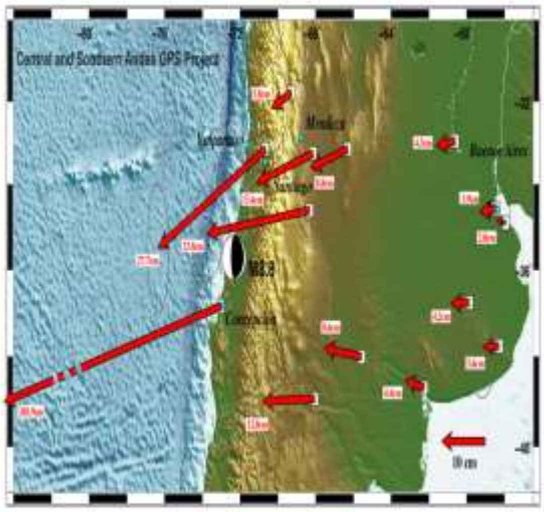

Fig. 4 – GPS coseismic horizontal displacement after El Maule 2010 earthquake showing 303.9 centimeters at the coast of Concepción, close to ENAP Refinery. [https://www.soest.hawaii.edu/ soest_web/soest.news_chile_feb2010_eq.htm].

3. Application of the “Backward Seismic Analysis” Method (BSA)

The BSA method consists in evaluating the seismic behavior of steel tanks, considering the characteristics of the tank in operation during the earthquake: general geometry and plate thicknesses, filling height, types of soil foundation, design codes used, seismic records, seismic directivity, observed damage, buckling shell and collapses. The tanks that have been damaged during major earthquakes were designed with the most recognized design codes and which are theoretically based on the Housner model, which together with the experimental models (shaking tables) do not reflect the real behavior of the tanks during earthquakes, since they do not meet the following hypotheses: effect of the thin shell, behavior of the liquid (laws of similarity), imperfections in shell plates reducing the allowable stresses in the shell, real conditions of foundation soil, soil-structure-liquid effect and seismic directivity.

3.1. Description of the Method

The BSA method is based on real information on the seismic behavior of steel tanks, allowing them to be classified according to their dimensions and slenderness, within safe ranges with minor damages, considerable and repairable damages up to values with a high risk of collapse. To apply this method the following information of the tanks is necessary:

- Dimensions (D, H) and thickness of the shell.
- Types of foundations and anchor systems.
- Foundation soil properties.
- Type of liquid stored.
- Levels of filling at the time of the earthquake.
- Seismicity and maximum accelerations (PGA) of the tank site areas.
- Damages observed during earthquakes.
- Weight and roof characteristics: conical, floating, dome.
- Design criteria and codes used.
- Engineering drawings and As Built.

3.2. Background Classification for Backward Seismic Analysis

This section analyzes historical cases of major earthquakes in Chile and the United States, being classified according to their tectonic failure mechanisms for subductive and cortical earthquakes. Table 1 summarizes base information with characterizations of tanks in real operating conditions during Chilean earthquakes of great magnitude, with results of the BSA studies and their seismic response. With the information collected from process plants and refineries, the state and post-seismic behavior of a series of steel tanks has been evaluated, especially considering the vertical components in the design of anchors and seismic response with long periods for convective mode. The response of tanks of different dimensions and slenderness relationships was studied where the impulsive or convective response predominates according to their slenderness relationship. The results obtained from this paper could be updated and adjusted with additional information such as those used in the doctoral thesis of D´Amico & Buratti [12] which considers a database of 3026 steel tanks for generate fragility curves. It should be mentioned that in this doctoral thesis, previous works by Pineda & Saragoni from Backward Seismic Analysis studies have been considered. Below is the nomenclature of table 1:

City: tank location		**Mag.: Magnitude of the Earthquake**		**Content**		**Design Information**	
Refineria de Con Con	RPC-Chile	**Seis.: Seismicity**		Gasoline	GAS	Liquid Density	G
Interacid Plant	INT-Chile	Subduction	SD	Nafta	NAF	Tank Diameter	D
Los Lirios Plant	LL-Chile	Cortical	CT	Solvent	SOL	Shell Height	H
Santiago International Airport	SIA-Chile	focal distance = 3.5km	CT(1)	Fuel Oil	FO	Maximum Height	H_{max}
PETROX	PT-Chile	focal distance = 45km	CT(2)	Slop	SL	Filling Height	H_{fill}
ENAP	ENP-Chile	focal distance = 25km	CT(3)	Asphalt	AS	Shell Thickness	t
Compañia de Acero del Pacifico	CAP-Chile	focal distance = 7.7km	CT(4)	Kerosene	KS	Thcikness Bottom Plate	tb
San Vicente International Terminal	SVIT-Chile	focal distance = 7.7km	CT(5)	Sulfuric Acid	SA	Design Criteria	DC
Anchorage	ANC-US	focal distance = 13km	CT(6)	Drinking Water	DW	**Damage Level**	
Nikiski	NIK-US	focal distance = 20km	CT(7)	Metil-ter-butil-éter	MTBE	Buckling Shell Lower	BSL
Seward	SEW-US	focal distance = 21km	CT(8)	Diesel	DS	Buckling Shell Upper	BSU
Long Beach	LB-US	**TAG: Tank Designation**		Tar	TAR	Undamaged	U
Kern/Pentland	KP-US	**Roof / Anchorage:**		Turbine Fuel	TF	Horizontal Sliding	HS
Kern/Emidio	KE-US	Floating	FL	No Information	NI	Bottom Lifted	BL
Rose	RO-US	Conical	CN	Jet Fuel	JF	Fail Shell-Roof	FSR
Grapevine	GP-US	**Anc.: Anchor Type**				Collapse	CL
Lebec	LB-US	**Ep.: Epicenter**				Roof Damage	RD
Paloma Plant	PP-US	Algarrobo	ALG			Sloshing Impact	SI
San Fernando	SF-US	Tocopilla	TOC			Burning	B
Imperial Valley	IV-US	El Maule	EM			Column/Beams Damages	CB
Landers	LD-US	Alaska	ALA			Bottom Settlement	BST
Coalinga	COA-US	United Sates	US				
Loma Prieta	LP-US						
Northridge	NR						

Table 1 – Characteristics and Behavior in Tanks During Earthquakes of Great Magnitude

İtem	Loc.	Year	Ep.	Mag.	Seism.	TAG	Cont.	G	D(m)	H(m)	D/H	HLL(m)	VL	t	tf	Cr	Anc.	Roof	Damage	DC	Version	HS (mm)	BL (mm)
1	RPC	1985	ALG	7.8	SD	T-326A	GAS	0,75	12,96	12,2	1,06	10,61	1609	6,05	9	0	no	FL	BSL	API	1988	----	----
2	RPC	1985	ALG	7.8	SD	T-326B	GAS	0,75	12,96	12,2	1,06	10,61	1609	6,05	9	0	no	FL	BSL	API	1988	----	----
3	RPC	1985	ALG	7.8	SD	T-418A	NAF	0,8	18,28	12,2	1,50	11,23	3202	8,15	9	0	no	FL	BSL	API	1988	----	----
4	RPC	1985	ALG	7.8	SD	T-552	SOL	0,67	11,18	12,2	0,92	11,56	1198	6,45	9	0	no	FL	BSL	API	1988	----	----
5	RPC	1985	ALG	7.8	SD	T-407A	FO	0,75	13,72	12,2	1,12	11,56	1804	7,45	9	0	no	CN	BSL	API	1988	----	----
6	RPC	1985	ALG	7.8	SD	T-320A	FO	0,75	11,18	12,2	0,92	10,42	1198	6,4	9	0	no	CN	BSL	API	1988	----	----
7	RPC	1985	ALG	7.8	SD	T-4001A	SL	0,75	11,18	12,2	0,92	11,15	1198	7,25	9	0	no	CN	BSL	API	1988	----	----
8	RPC	1985	ALG	7.8	SD	T-405A	AS	0,75	18,28	12,2	1,50	11,33	3202	9,55	9	0	no	CN	BSL	API	1988	----	----
9	RPC	1985	ALG	7.8	SD	T-420A	KS	0,75	15,84	11,6	1,37	1,94	2286	7,94	9	0	no	CN	BSL	API	1988	----	----
10	RPC	1985	ALG	7.8	SD	T-301A	KS	0,75	15,24	9,8	1,56	3,26	1779	6,15	9	0	no	CN	BSL	API	1988	----	----
11	RPC	1985	ALG	7.8	SD	T-422A	KS	0,75	22,34	12,2	1,83	7,88	4782	11,15	9	0	no	CN	BSL	API	1988	----	----
12	RPC	1985	ALG	7.8	SD	T-402	GAS	0,75	22,4	12,2	1,84	10,80	4808	10,3	9	0	no	CN	U	API	1988	----	----
13	INT	2007	TOC	7,7	SD	TK-201	SA	1,83	35	14,5	2,41	9,10	13951	25	10	0	no	CN	BSU, HS, BL	API	1988	10	70-80
14	INT	2007	TOC	7,7	SD	TK-202	SA	1,83	35	14,5	2,41	0,00	13951	25	10	0	no	CN	U	API	1988	----	15
15	INT	2007	TOC	7,7	SD	TK-203	SA	1,83	35	14,5	2,41	5,12	13951	25	10	0	no	CN	U	API	1988	----	----
16	LL	2010	EM	8,8	SD	E1	SA	1,834	16,5	12,4	1,33	12,40	2651	16	9	0	yes	CN	U	API	1988	----	----
17	LL	2010	EM	8,8	SD	E2	SA	1,834	8	3,7	2,16	3,70	186	8	9	0	yes	CN	U	API	1988	----	----
18	SIA	2010	EM	8,8	SD	TK-5	DW	1	15	14,0	1,07	14,00	2474	5	5	0	no	CN	CL	API	1998	----	----
19	SIA	2010	EM	8,8	SD	TK-1	FO	0,75	12	16,0	1,33	7,98	1805	10	8	0	yes	CN	U	API	1988	----	----
20	SIA	2010	EM	8,8	SD	TK-2	FO	0,75	12	16,0	1,33	7,98	1805	10	8	0	yes	CN	U	API	1988	----	----
21	SIA	2010	EM	8,8	SD	TK-3	FO	0,75	12	16,0	1,33	7,98	1805	10	8	0	yes	CN	U	API	1988	----	----
22	SIA	2010	EM	8,8	SD	TK-4	FO	0,75	15	20,0	1,33	9,98	3525	10	8	0	yes	CN	U	API	1988	----	----
23	SVIT	2010	EM	8,8	SD	TK	DS	0,86	11,6	12,0	1,33	12,00	1268	10	6	0	yes	CN	U	API	1961	----	----
24	ENP	2010	EM	8,8	SD	T-3009	DS	0,86	33,258	14,3	2,32	14,33	12444	36	6	0	no	CN	U	API	1978	----	----
25	ENP	2010	EM	8,8	SD	T-3010	DS	0,86	33,258	14,3	2,32	14,33	12444	36	6	0	no	CN	U	API	1978	----	----
26	ENP	2010	EM	8,8	SD	T-3020	FO	0,8	45,72	12,2	3,75	12,19	20016	22	6	0	no	CN	U	API	1961	----	----
27	ENP	2010	EM	8,8	SD	T-3021	FO	0,8	45,72	12,2	3,75	12,19	20016	22	6	0	no	CN	U	API	1961	----	----
28	ENP	2010	EM	8,8	SD	T-3022	FO	0,8	45,72	12,2	3,75	12,19	20016	22	6	0	no	CN	U	API	1961	----	----
29	ENP	2010	EM	8,8	SD	T-3023	FO	0,8	45,72	12,2	3,75	12,19	20016	22	6	0	no	CN	U	API	1961	----	----
30	ENP	2010	EM	8,8	SD	T-3156	GAS	1	30,48	13,4	2,27	13,41	9785	12	12	0	yes	CN	U	API	1998	----	----
31	ENP	2010	EM	8,8	SD	T-3152	GAS	1	22,352	9,8	2,27	9,85	3864	10	6	0	no	CN	U	API	1988	----	----
32	ENP	2010	EM	8,8	SD	T-3153	GAS	1	22,352	9,8	2,27	9,85	3864	10	6	0	no	CN	U	API	1988	----	----
33	ENP	2010	EM	8,8	SD	T-3154	GAS	1	22,352	9,8	2,27	9,85	3864	10	6	0	no	CN	U	API	1988	----	----
34	ENP	2010	EM	8,8	SD	T-3155	GAS	1	22,352	9,8	2,27	9,85	3864	10	6	0	no	CN	U	API	1988	----	----
35	ENP	2010	EM	8,8	SD	T-3157	GAS	1	30,48	13,4	2,27	13,41	9785	12	12	0	yes	CN	U	API	1998	----	----
36	ENP	2010	EM	8,8	SD	T-3252	GAS	1	30,48	13,4	2,27	13,41	9785	12	12	0	yes	CN	U	API	1998	----	----
37	ENP	2010	EM	8,8	SD	T-3257	GAS	0,75	30,501	18,4	1,66	18,42	13455	14,6	8	0	no	CN	U	API	1998	----	----
38	ENP	2010	EM	8,8	SD	T-3258	GAS	0,75	30,501	18,4	1,66	18,42	13455	14,6	8	0	no	CN	U	API	1998	----	----
39	ENP	2010	EM	8,8	SD	T-3260	FO	0,8	45,72	12,2	3,75	12,19	20016	22	6	0	no	CN	U	API	1961	----	----
40	ENP	2010	EM	8,8	SD	T-3261	FO	0,8	45,72	12,2	3,75	12,19	20016	22	6	0	no	CN	U	API	1961	----	----
41	ENP	2010	EM	8,8	SD	T-3262	FO	0,8	45,72	12,2	3,75	12,19	20016	22	6	0	no	CN	U	API	1961	----	----
42	ENP	2010	EM	8,8	SD	T-3425	GAS	1	30,48	13,4	2,27	13,41	9785	12	12	0	yes	CN	U	API	1988	----	----
43	ENP	2010	EM	8,8	SD	T-3426	GAS	1	30,48	13,4	2,27	13,41	9785	12	12	0	yes	CN	U	API	1988	----	----
44	ENP	2010	EM	8,8	SD	T-3427	GAS	1	30,48	13,4	2,27	13,41	9785	12	12	0	yes	CN	U	API	1988	----	----
45	ENP	2010	EM	8,8	SD	T-3428	DS	0,86	45,72	15,2	3,00	15,22	24981	17,6	8	0	no	CN	U	API	2005	----	----
46	ENP	2010	EM	8,8	SD	T-3450	FO	0,8	45,72	12,2	3,75	12,19	20016	22	6	0	no	CN	U	API	1961	----	----
47	ENP	2010	EM	8,8	SD	T-3451	FO	0,8	45,72	12,2	3,75	12,19	20016	22	6	0	no	CN	U	API	1961	----	----
48	ENP	2010	EM	8,8	SD	T-3506	FO	0,8	45,72	12,2	3,75	12,19	20016	22	6	0	no	CN	U	API	1961	----	----
49	ENP	2010	EM	8,8	SD	T-3507	DS	0,86	45,72	12,2	3,75	12,19	20016	22	6	0	no	CN	U	API	1961	----	----
50	ENP	2010	EM	8,8	SD	T-6010	FO	0,8	67	14,6	4,58	13,72	51580	36	17	0	no	FL	U	API	1988	----	----
51	ENP	2010	EM	8,8	SD	T-6020	FO	0,8	67	14,6	4,58	13,72	51580	36	17	0	no	FL	U	API	1988	----	----
52	ENP	2010	EM	8,8	SD	T-6030	FO	0,8	67	14,6	4,58	3,66	51580	36	17	0	no	FL	U	API	1988	----	----
53	CAP	2010	EM	8,8	SD	N°1 y 2	TAR	0,8	3,658	6,1	0,60	6,10	64	6,5	6,5	0	no	CN	U	API	1998	----	----
54	ANC	1964	ALA	9,2	SD	B	FO	0,8	30,5	9,8	3,13	9,76	7131	12	11	0,36	no	CN	FSR, CB	NI	----	----	----
55	ANC	1964	ALA	9,2	SD	C	TF	0,8	13,725	9,8	1,41	9,76	1444	5,3	9	0,16	no	CN	RD, FSR, BSL	NI	----	----	----
56	ANC	1964	ALA	9,2	SD	D	FO	0,8	36,6	9,8	3,75	9,76	10268	14	14	0,42	no	CN	RD, FSR, CB	NI	----	----	----
57	ANC	1964	ALA	9,2	SD	E	NI	0,8	36,6	9,8	3,75	0,98	10268	14	14	0	no	CN	U	NI	----	----	----
58	ANC	1964	ALA	9,2	SD	F	NI	0,8	36,6	9,8	3,75	0,98	10268	14	14	0	no	CN	U	NI	----	----	----
59	ANC	1964	ALA	9,2	SD	G	NI	0,75	33,55	9,8	3,44	0,98	8628	14	14	0	no	CN	U	NI	----	----	----
60	ANC	1964	ALA	9,2	SD	H	NI	0,8	27,45	11,0	2,50	6,40	6498	13,2	11	1,18	no	CN	U	NI	----	----	----
61	ANC	1964	ALA	9,2	SD	I	FO	0,8	16,775	7,0	2,39	7,02	1550	6,4	9	0,37	no	CN	RD, FSR	NI	----	----	----
62	ANC	1964	ALA	9,2	SD	J	NI	0,8	9,15	12,2	0,75	12,20	802	4,8	9	0,13	no	CN	BSL	NI	----	----	----
63	ANC	1964	ALA	9,2	SD	K	NI	0,8	9,15	12,2	0,75	12,20	802	4,8	9	0,13	no	CN	BSL	NI	----	----	----
64	ANC	1964	ALA	9,2	SD	L	NI	0,8	9,15	12,2	0,75	12,20	802	4,8	9	0,13	no	CN	BSL	NI	----	----	----
65	ANC	1964	ALA	9,2	SD	N	NI	0,8	12,81	12,2	1,05	12,20	1572	5,8	9	0,14	no	CN	BSL	NI	----	----	----
66	ANC	1964	ALA	9,2	SD	O	NI	0,8	6,1	12,2	0,50	12,20	357	4,8	9	0,19	no	CN	BSL	NI	----	----	----
67	ANC	1964	ALA	9,2	SD	T	NI	0,8	48,8	17,1	2,86	17,08	31946	33	9	0,57	no	CN	CB	NI	----	----	----
68	ANC	1964	ALA	9,2	SD	U	NI	0,8	48,8	17,1	2,86	17,08	31946	33	9	0,57	no	CN	U	NI	----	----	----
69	NIK	1964	ALA	9,2	SD	R200	DW	1	9,15	14,6	0,63	14,64	963	5,3	9	0,09	no	CN	CL	NI	----	----	----
70	ANC	1964	ALA	9,2	SD	AA5	JF	0,8	8,54	12,2	0,70	12,20	699	4,8	9	0,14	no	CN	CL	NI	----	----	----

Table 1 – Characteristics and Behavior in Tanks During Earthquakes of Great Magnitude (Cont.)

İtem	Loc.	Year	Ep.	Mag.	Seism.	TAG	Cont.	G	D(m)	H(m)	D/H	HLL(m)	VL	t	tf	Cr	Anc.	Roof	Damage	DC	Version	HS (mm)	BL (mm)
71	ANC	1964	ALA	9,2	SD	AA7	JF	0,8	12,2	13,0	0,94	12,96	1515	6,05	9	0,19	no	CN	BSL	NI	----	----	----
72	SEW	1964	ALA	9,2	SD	0	FO	0,8	9,15	10,7	0,86	10,68	702	4,8	9	0,16	no	CN	BSL, B	NI	----	----	----
73	NIK	1964	ALA	9,2	SD	R140	NI	0,8	14,945	14,6	1,02	14,64	2568	9	9	0,19	no	CN	BSL, BL	NI	----	----	50,8
74	NIK	1964	ALA	9,2	SD	R162	NI	0,8	27,45	14,6	1,88	10,98	8664	16	11	0,57	no	CN	FSR, RD	NI	----	----	----
75	NIK	1964	ALA	9,2	SD	R163	NI	0,8	27,45	14,6	1,88	10,98	8664	16	11	0,57	no	CN	FSR, RD	NI	----	----	----
76	NIK	1964	ALA	9,2	SD	R100	NI	0,75	34,16	17,1	2,00	12,81	15654	14	11	0	no	CN	RD	NI	----	----	----
77	NIK	1964	ALA	9,2	SD	R120	NI	0,75	21,35	14,6	1,46	10,98	5241	13	9	0	no	CN	RD	NI	----	----	----
78	NIK	1964	ALA	9,2	SD	R110	NI	0,75	43,92	17,1	2,57	12,81	25876	30	9	0	no	CN	RD, SI	NI	----	----	----
79	ANC	1964	ALA	9,2	SD	AA4	NI	1	3,2025	9,2	0,35	3,05	74	4,8	9	0	no	CN	HS	NI	----	1524	----
80	LB	1933	US	6,4	CT(1)	A	DW	1	28,9	8,8	3,28	8,62	5773	4,8	11	0	no	CN	BSL, FSR	NI	----	----	----
81	LB	1933	US	6,4	CT(2)	C	DW	1	45,4	19,0	2,39	14,50	30758	9	9	0	no	CN	BSL	NI	----	----	----
82	KP	1952	US	7,5	CT(3)	500x81	FO	0,8	34,9	9,1	3,82	1,22	8744	6	11	0	no	CN	BSL	NI	----	----	----
83	KP	1952	US	7,5	CT(3)	500x82	FO	0,8	34,9	9,1	3,82	5,80	8744	6	11	0	no	CN	U	NI	----	----	----
84	KP	1952	US	7,5	CT(3)	500x83	FO	0,8	34,9	9,1	3,83	0,79	8715	6	11	0	no	CN	SI, BSL	NI	----	----	----
85	KP	1952	US	7,5	CT(3)	500x84	FO	0,8	34,9	9,1	3,82	5,52	8744	6	11	0	no	CN	IS	NI	----	----	----
86	KP	1952	US	7,5	CT(3)	500x85	FO	0,8	34,9	9,1	3,86	2,87	8657	6	11	0	no	CN	U	NI	----	----	----
87	KP	1952	US	7,5	CT(3)	500x86	FO	0,8	34,9	9,1	3,84	8,30	8686	6	11	0	no	CN	IS, AF	NI	----	----	----
88	KE	1952	US	7,5	CT(4)	37003	FO	0,8	28,71	9,2	3,12	2,68	5956	5	11	0	no	CN	IS	NI	----	----	----
89	KE	1952	US	7,5	CT(4)	37014	FO	0,8	28,71	9,1	3,14	5,73	5917	5	11	0	no	CN	IS	NI	----	----	----
90	KE	1952	US	7,5	CT(4)	550x79	FO	0,8	34,99	9,1	3,84	1,40	8760	6	11	0	no	CN	IS	NI	----	----	----
91	KE	1952	US	7,5	CT(4)	800x11	FO	0,8	35,72	12,7	2,80	3,08	12767	6	14	0	no	CN	IS	NI	----	----	----
92	RO	1952	US	7,5	CT(5)	37004	FO	0,8	28,71	9,2	3,13	6,04	5936	5	14	0	no	CN	IS	API	----	----	----
93	RO	1952	US	7,5	CT(5)	37015	FO	0,8	28,71	9,2	3,13	2,26	5936	5	14	0	no	CN	IS	API	----	----	----
94	GP	1952	US	7,5	CT(6)	37005	FO	0,8	28,71	9,2	3,13	6,50	5936	5	14	0	no	CN	IS	API	----	----	----
95	GP	1952	US	7,5	CT(6)	37016	FO	0,8	28,71	9,2	3,13	0,73	5936	5	14	0	no	CN	IS	API	----	----	----
96	LB	1952	US	7,5	CT(7)	37006	FO	0,8	28,65	9,2	3,11	4,82	5931	5	14	0	no	CN	IS	API	----	----	----
97	LB	1952	US	7,5	CT(7)	370x13	FO	0,8	28,93	9,1	3,19	4,82	5969	5	14	0	no	CN	IS	API	----	----	----
98	LB	1952	US	7,5	CT(7)	55021	FO	0,8	34,93	9,1	3,83	3,78	8730	6	14	0	no	CN	IS	API	----	----	----
99	LB	1952	US	7,5	CT(7)	55022	FO	0,8	34,93	9,1	3,83	1,68	8730	6	14	0	no	CN	IS	API	----	----	----
100	LB	1952	US	7,5	CT(7)	55047	FO	0,8	34,93	9,1	3,82	0,98	8759	6	14	0	no	CN	IS	API	----	----	----
101	LB	1952	US	7,5	CT(7)	80105	FO	0,8	35,69	12,7	2,80	0,00	12745	6	14	0	no	CN	IS	API	----	----	----
102	PP	1952	US	7,5	CT(8)	TK-1	FO	0,8	36,6	6,3	5,86	6,25	6576	6	14	0	no	CN	IS	API	----	----	----
103	PP	1952	US	7,5	CT(8)	TK-2	FO	0,8	23,8	8,9	2,67	8,93	3973	5	14	0	no	CN	IS	API	----	----	----
104	PP	1952	US	7,5	CT(8)	TK-3	FO	0,8	23,8	13,5	1,76	13,50	6006	5	14	0	no	CN	IS	API	----	----	----
105	PP	1952	US	7,5	CT(8)	TK-4	FO	0,8	36,6	8,9	4,11	8,90	9364	5	14	0	no	CN	IS	API	----	----	----
106	SF	1971	US	6,7	SD	TK-1	FO	0,8	31	11,0	2,82	10,34	8302	12	0	0,32	yes	CN	U	API	----	----	----
107	SF	1971	US	6,7	SD	TK-2	FO	0,8	17	12,0	1,42	12,00	2724	5	14	0	yes	CN	BSL	API	----	----	----
108	SF	1971	US	6,7	SD	TK-1	FO	0,8	16,6	8,6	1,93	8,60	1861	5	0	0	yes	CN	U	API	----	----	----
109	SF	1971	US	6,7	SD	TK-2	FO	0,8	29,2	11,2	2,61	9,21	7500	14	0	0,49	yes	CN	U	API	----	----	----
110	SF	1971	US	6,7	SD	TK-1	DW	1	6,2	6,2	1,00	6,20	187	4	0	0	yes	CN	BSL	AWWA	----	----	----
111	SF	1971	US	6,7	SD	TK-2	DW	1	6,2	6,2	1,00	6,20	187	4	0	0	yes	CN	BSL	AWWA	----	----	----
112	SF	1971	US	6,7	SD	TK-1	FO	0,8	29	13,0	2,23	12,35	8587	6	0	0	no	CN	U	API	----	----	----
113	SF	1971	US	6,7	SD	TK-1	FO	0,8	17	13,8	1,23	13,11	3132	5	0	0	no	CN	RD	API	----	----	----
114	SF	1971	US	6,7	SD	TK-1	JF	0,75	18,5	12,2	1,52	12,20	3279	5	0	0	no	CN	BSL	API	----	----	----
115	SF	1971	US	6,7	SD	TK-2	JF	0,75	18,5	12,2	1,52	12,20	3279	5	0	0	no	CN	BSL	API	----	----	----
116	SF	1971	US	6,7	SD	TK-3	JF	0,75	18,5	12,2	1,52	12,20	3279	6	0	0	no	CN	BSL	API	----	----	----
117	SF	1971	US	6,7	SD	TK-1	JF	0,75	37	12,2	3,03	12,20	13118	6	0	0	no	CN	U	API	----	----	----
118	SF	1971	US	6,7	SD	TK-2	JF	0,75	37	12,2	3,03	12,20	13118	6	0	0	no	CN	U	API	----	----	----
119	SF	1971	US	6,7	SD	TK	NI	1	12,81	9,2	1,40	9,15	1179	4,8	0	0,13	yes	CN	U	API	----	----	----
120	SF	1971	US	6,7	SD	TK	NI	1	17,08	9,8	1,75	9,76	2236	6,4	0	0,18	yes	CN	BSL	API	----	----	----
121	SF	1971	US	6,7	SD	TK	NI	0,8	9,76	12,2	0,80	12,20	913	9,4	0	0,23	yes	CN	U	API	----	----	----
122	SF	1971	US	6,7	SD	TK	NI	1	19,825	12,2	1,63	12,20	3766	9,4	0	0,24	yes	CN	BSL	API	----	----	----
123	IV	1979	US	6,5	SD	TK-1	FO	0,8	41,2	13,7	3,01	13,70	18264	NI	0	0	no	CN	RD	API	----	----	----
124	IV	1979	US	6,5	SD	TK-2	FO	0,8	22,3	6,1	3,66	6,10	2382	NI	0	0	no	CN	RD	API	----	----	----
125	IV	1979	US	6,5	SD	TK-1	GAS	1	24,2	14,6	1,66	6,19	6715	NI	0	0	no	FL	U	API	----	----	----
126	IV	1979	US	6,5	SD	TK-2	GAS	1	24,4	14,6	1,67	7,14	6827	NI	0	0	no	FL	U	API	----	----	----
127	IV	1979	US	6,5	SD	TK-3	GAS	1	20,4	12,3	1,66	4,79	4020	NI	0	0	no	CN	U	API	----	----	----
128	IV	1979	US	6,5	SD	TK-4	GAS	1	14,6	14,6	1,00	7,78	2444	NI	0	0	yes	FL	U	API	----	----	----
129	IV	1979	US	6,5	SD	TK-5	GAS	1	14,6	14,6	1,00	10,64	2444	NI	0	0	yes	FL	BSL	API	----	----	----
130	IV	1979	US	6,5	SD	TK-6	GAS	1	13	12,2	1,07	4,64	1619	NI	0	0	yes	FL	U	API	----	----	----
131	IV	1979	US	6,5	SD	TK-7	GAS	1	13	12,2	1,07	4,79	1619	NI	0	0	yes	CN	U	API	----	----	----
132	IV	1979	US	6,5	SD	TK-8	GAS	1	24,7	14,6	1,69	12,02	6996	NI	0	0	no	FL	U	API	----	----	----
133	IV	1979	US	6,5	SD	TK-9	GAS	1	13	12,2	1,07	7,87	1619	NI	0	0	yes	FL	U	API	----	----	----
134	IV	1979	US	6,5	SD	TK-10	GAS	1	13	12,2	1,07	9,30	1619	NI	0	0	yes	FL	U	API	----	----	----
135	IV	1979	US	6,5	SD	TK-11	GAS	1	14,2	12,2	1,16	10,49	1932	NI	0	0	yes	CN	U	API	----	----	----
136	IV	1979	US	6,5	SD	TK-12	GAS	1	13	12,2	1,07	10,52	1619	NI	0	0	yes	FL	U	API	----	----	----
137	IV	1979	US	6,5	SD	TK-13	GAS	1	12,6	14,9	0,85	13,27	1858	NI	0	0	yes	CN	BSL	API	----	----	----
138	IV	1979	US	6,5	SD	TK-14	GAS	1	14,7	14,9	0,99	9,12	2529	NI	0	0	yes	CN	U	API	----	----	----
139	IV	1979	US	6,5	SD	TK-15	GAS	1	15,2	14,9	1,02	9,09	2704	NI	0	0	yes	CN	U	API	----	----	----
140	IV	1979	US	6,5	SD	TK-16	GAS	1	14,8	14,9	0,99	12,17	2563	NI	0	0	yes	CN	BSL	API	----	----	----

3.3. Freeboard

In this work the heights of the seismic waves of the tanks of the database considered for 245 tanks of different dimensions were analyzed, applying the most used methods in the design and subsequent manufacture of tanks steel (see Figure 5), concluding that they show a great dispersion in the results. The differences between the values obtained are due to the fact that the ENDESA formula [13] does not consider the periods of vibration of the convective mode and seismicity of the area, being more conservative, in the equation proposed by NZSEE the seismic coefficients of the modes are considered convective with the spectrum of NCh2369 and in API 650-E seismic coefficients without spectral values have been considered. Considering the spectral values of NCh2369 in the NZSEE and API 650-E proposals, identical values of seismic wave heights are obtained, so it is recommended that they conform to local seismic conditions.

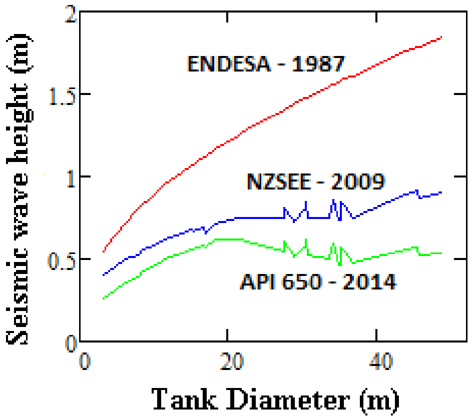

Fig. 5 - Variation of the seismic wave height by most used code.

Fig. 6 - Tank T-6020 with oil spill by insufficient freeboard. ENAP Bío Bío refinery. The Maule 2010 [14].

ENAP Refinery located in the city of Talcahuano there were two tanks that presented spills of the stored liquids, being necessary to evaluate the proposed formulas with the seismic characteristics of the areas along with a strict control of the filling of the tanks during their operation. The T-6020 tank in Figure 6 was 94% full, which exceeded the level of filling recommended by the proposals in Figure 5, presenting oil spills at about 270° perimeter on the shell. During the Illapel earthquake of magnitude Mw = 8.4 on September 26, 2015, the broadband accelerometer network measured displacements in the displacement spectrum at intervals of 10 to 15 seconds. Considering the tanks that have similar convective periods measured instrumentally, the effects in different equations proposed for the determination of the seismic wave height (sloshing) were analyzed, concluding that the proposed equations in the design codes are underestimated, presenting important differences and in addition they are not respected in the usual filling during operation.

3.4. Horizontal Sliding in Unanchored Tanks

One common failure in unanchored tanks during earthquakes is the horizontal sliding due to the inertial forces of the masses of tanks-liquid system. The BSA method performed in this work for coastal zones of subductive earthquakes, have determined that the sliding is also due to coseismic tectonic displacements measured in meters by means of GPS. Figure 7 shows displacement spectral recorded by instruments and refers to vibratory movements, while the values obtained from Equation (1) and the spills indicated in Figure 6 refer to inertial behavior in the coseismic direction. Table 2 shows horizontal sliding of tanks observed in some earthquakes ([5], [6] and [7]), which have been used to propose Equation (1) for coseismic sliding estimated values only for subduction earthquakes. Unidirectional coseismic sliding occur in the first 30 and 40 seconds of the seismic movement, with quasi-static characteristics, generating inertial forces mainly in the opposite direction of the movement. These forces are not currently considered in the design codes, since they overlap the vibratory forces generated by the seismic vibration of the ground, measured through the spectra of acceleration responses.

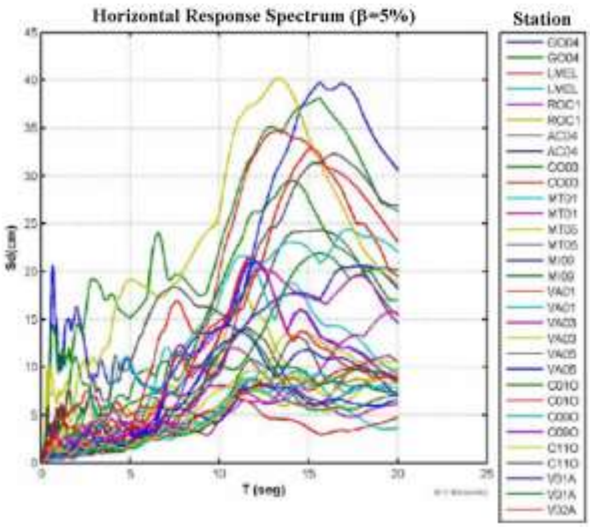

Fig. 7 – Response spectrum for horizontal displacements. Interplate subductive earthquake of Chile 2015, Illapel.

Fig. 8 – Tank TK-201 with horizontal sliding, Tocopilla 2007.

Table 2 – Horizontal Sliding Observed in Tanks ([5], [6]).

Earthquake	Magnitude	Tectonic	S_h (mm)	D (mm)	H (mm)
Alaska 1964	9.2	Subduction	1524	3200	9144
Tocopilla 2007	7.7	Subduction	10	35000	14500
Landers 1992	7.3	Cortical	80	16500	7300

$$S[m] = -7.76 + 1.01M \quad ; \quad M \geq 7.7 \qquad (1)$$

S[m]: coseismic sliding in meters ; M: moment magnitude.

Table 2 contains information that is supported by Figure 8 and shows the horizontal slippage of a tank in operation during the Tocopilla 2007 earthquake.

3.5. Seismic Directivity

The effect of seismic directivity is incident on the seismic structural response of tanks in subductive earthquakes, because quasi-static landslides are generated perpendicular to the coastal edge, coinciding with the convergence direction of the Nazca Subducted plate, which confirms the directivity of the Chilean earthquakes. This seismic behavior has been observed in the tanks since the Chile Central 1985 earthquake, then during the Tocopilla subduction earthquake in 2007 there were horizontal sliding perpendicular to the coast as shown in Figure 9. Figure 10 shows the effects of seismic directivity in tanks located in areas close to the asperities of the South American plate, due to the interaction between tectonic plates, compressions are generated, releasing unidirectional coseismic displacements perpendicular to the coastal edge in a few seconds. Figures 11 and 12 show the tanks located in the gas facilities of San Vicente Port during the El Maule 2010 earthquake, the tank located on the west side of Figure 11 remained with a vertical inclination of 1 degree perpendicular to the coastal edge, confirming that in the Chilean earthquakes seismic directivity predominates in the direction of subduction. This tank (D = 11.6m H = 12m) was built in 1968, was full of liquid at the time of the earthquake and was anchored, for this reason it had good seismic behavior. Figures 13 and 14 show the effects of the 2010 El Maule earthquake in the tanks located in the Bío Bío refinery, which were oriented in the N-S direction.

Fig. 9 - Tank located in Mejillones during the Tocopilla 2007 earthquake, buckling in the shell perpendicular to the coast.

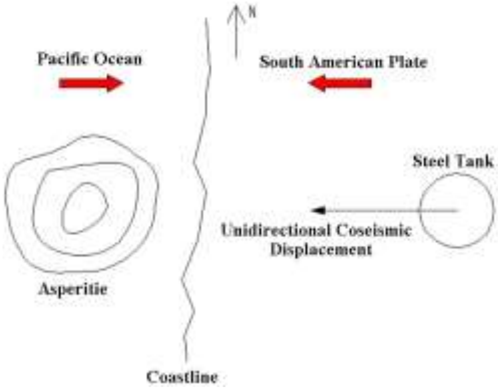

Fig- 10 - Effects of asperities in steel tanks located on coastal subduction edges.

Fig. 11 - Gas storage tanks in Puerto San Vicente. El Maule 2010 earthquake. Red arrow indicates seismic directivity.

Fig. 12 - Tank with inclination perpendicular to the coastal edge. San Vicente Port, El Maule 2010 earthquake.

Fig. 13 - Oil storage tanks at the ENAP Bío Bío Refinery during the El Maule 2010 earthquake.

Fig. 14 - Tank with spillage perpendicular to the coastal edge. ENAP Bio Bio refinery, El Maule 2010 earthquake.

Figure 14 shows the spillage in the W-E direction and perpendicular to the coastline, confirming the seismic directivity of Chilean subductive earthquakes. This effect is an incident in the seismic response of the tanks with predominance in the convective masses.

3.6. Stresses in Shell of Anchored and Unanchored Tanks

The compression stresses in the shell are conditioned by the slenderness ratios and anchoring systems that they have, because they control the impact of the seismic forces and the vertical lifting of the shell. Considering that some design codes provide recommendations for the calculation of the allowable stresses that are not consistent with these principles, the values obtained present variations that need to be identified prior to the design, together with the effect of imperfections in the shell plates due to defects of manufacturing, during transport or assembly, this being a factor reducing the allowable stresses. Figure 15 shows the compressive stresses calculated with the API-E code (1988), working (F_c) and allowable (σ_c), in the shell of the tanks located in the Con Con refinery during the Chile Central 1985 earthquake. The earthquakes were mostly full of liquids and without anchors. The results obtained from the BSA in this work conclude that the design criteria of API 650-E in its 1988 version underestimated the actual compression stresses in the shell for non-anchored tanks, since lower working values than the allowable ones are obtained, the tanks were unstable and they raised at the base, so they should have been anchored and modified their geometry. Since the tanks designed with the API 650-E standard presented important failures such as "elephant's foot buckling" in shell, it is necessary to review their recommendations for the seismic design. Figure 16 shows the variations in the allowable stresses in the shell applying the main codes and methods used in industrial projects for different diameters of tanks and should reduce the allowable stresses in plates with deformations due to manufacturing defects.

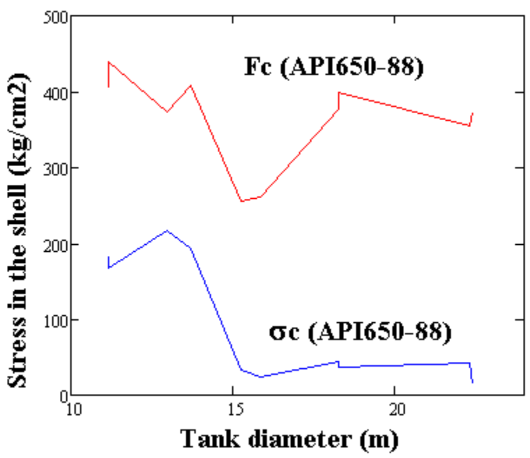

Fig. 15 - Analysis of compression stresses in the shell, Chile Central 1985 Earthquake.

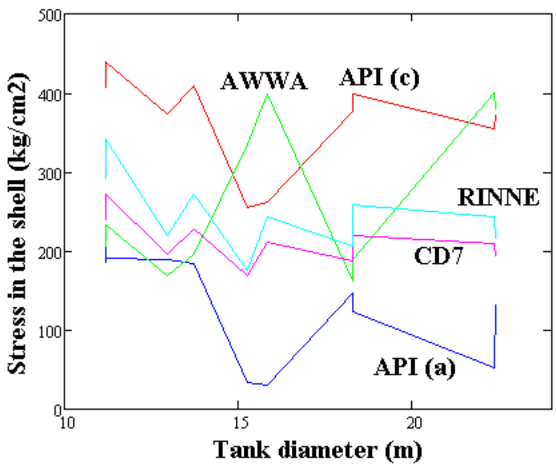

Fig. 16 – Variations of stresses in the shell of tanks with the most used methods.

Figure 16 shows the provisions of the most used methods for the seismic design of tanks were applied: API 650-E [1], AWWA D-100 [2], Rinne 1964 [15] and CD7-1994 [16]. A comparative analysis of the compression stresses according to API 650-E was also incorporated, being above all the allowable stresses according to these with anchorage requirements to ensure the stability of the tanks. This confirms the need to review design recommendations for unanchored tanks. Figures 17 and 18 show unanchored tanks designed with the API 650-E code, which showed "elephant's foot buckling" during the earthquakes in Chile in 1985 and 2007. Maximum values of seismic parameters of the site for different types of soils were considered, in addition to the updated structural response modification factors, since the Chilean standard NCh2369 in its 2003 version recommends using: R_i=R_c=4 for the impulsive mode and convective. The factor corresponding to the convective mode must be replaced by R_c=1, like that recommended by international codes for tanks design. It is important to consider a greater amount of undamaged tanks in seismic areas so as not to overestimate the damages, this is one of the reasons why the design codes do not reflect the real behavior of the tanks against earthquakes, which should be incorporated into new versions of the codes.

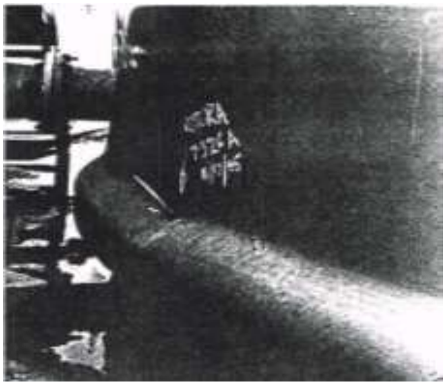

Fig. 17 – Elephant's Foot Buckling. Con Con Refinery, ENAP. Chile Central 1985 earthquake.

Fig. 18 – Tank for acid storage in Mejillones. Lower buckling of shell. Tocopilla earthquake in 2007.

4. Recommendations

The usual practices in the seismic design of steel tanks should be corrected to reduce the damages and risks of collapses. Subductive interplate earthquakes generate high components of vertical accelerations and horizontal sliding, the use of anchors is recommended to prevent damage and reduce convective seismic demand. The effects of imperfections in the shell should be considered to reduce the allowable stresses. Is proposed an equation to calculate the horizontal sliding of the unanchored tanks in subduction zones. For the calculation of the convective seismic response, the modification factor of the structural response Rc = 1 must be used, since the convective mass has seismic behavior with low levels of energy dissipation by non-linear behavior, in addition to predict the seismic response of the convective mass requires complex mathematical analysis and there is no creep in the liquid. The results proposed in this work must be complemented with field measurements of the earthquake seismic response for updating the proposed equations.

5. Conclusions

The Backward Seismic Analysis method for atmospheric steel tanks submitted to subduction earthquakes registered in Chile and the United States in the last 80 years is presented. It is concluded that the most used methodologies with recognized seismic design codes are insufficient in their recommendations, since the tanks have presented repeated failures and sometimes collapses during earthquakes considered design. It has been identified that the non-vibratory inertial effect is characteristic of mega subduction earthquakes in coastal areas, occurring simultaneously with high vertical accelerations of soil and generates horizontal displacements in the tanks that compromises the continuity of the operation, this phenomenon is not considered in seismic design codes for steel tanks. The Housner model used in the design codes presents important limitations in its hypotheses for seismic analysis and structural design, not considering site effects, seismic directivity and inertial forces, which explains the poor seismic behavior of the tanks. During major Chilean earthquakes (1985, 2007 and 2010), quasi-static horizontal sliding and buckling of shell of the tanks were generated, generated in a direction perpendicular to the coastline and coinciding with the direction of convergence of the Nazca plate in subduction, which confirms the effects of the seismic directivity of the Chilean earthquakes. It is concluded that there is no correlation between analytical theoretical models, experimental tests and what was observed with the BSA method, since the computational models do not consider the actual conditions of the tanks in operation, such as: effect of thin shell, liquid behavior (laws similarity), imperfections in shell, real soil conditions and effects of seismic directivity. The codes need to be updated, shell design criteria and anchor systems, since they apply theoretical models that are not calibrated.

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