

ANALYSIS OF THE INTENSITY TENSOR IN CHILE SUBDUCTION EARTHQUAKES

P. Pineda^{(1), (2)}

⁽²⁾ Consultant in Earthquake Engineering, Santiago, Chile. patricio.pineda@ppning.com

⁽¹⁾ M.Sc. in Seismic Engineering, University of Chile, Santiago, Chile. ppningen@gmail.com

Abstract

The intensity tensor analyzed in this work contains the components of the Arias Intensity for a series of acceleration records according to the Oxyz directions of a given reference system, which is oriented according to the East-West, North-South and Vertical directions, for the most representative subduction earthquakes in Chile. This formulation establishes that the first invariant of the destructiveness potential tensor is the damage measure, considering the vertical component of the records and incorporating the local intensity of zero crossings. The main values of this tensor can be related to establish a directivity index that characterizes subduction earthquakes, associated with several factors such as: type of mechanism of the seismic source, types of predominant seismic waves, effects of dynamic amplification of the soil. The relationships obtained from the degree of coupling of the horizontal and vertical components of the seismic records, combining some characteristics of earthquakes, are important for estimating the three-dimensional seismic response of the structures. The definition of intensity tensor used in this work is based on the parameter known as Arias intensity (Arias et al., 1969), based on instrumental records of strong ground motion. With this definition, the Destructiveness Potential (Araya and Saragoni, 1984) is also evaluated for the cases under study of subductive earthquakes, in order to estimate the characteristics of future earthquakes together with the effects on the structures, widely used in hazard seismic analysis. In this work, the records of the main subductive earthquakes in Chile are used to evaluate the invariants of the intensity tensor and determine the associated directivity indices.

Keywords: Tensor, Arias Intensity, Directivity, Earthquake, Subduction, Destructiveness Potential.

1. Introduction

In the preparation of seismic hazard analysis is essential a good prediction of the characteristics of earthquakes to assess its impact on structural design and propose effective recommendations. For this, it is necessary to consider the earthquake severity measures and their relationship with the expected damage, for which there are several methods that have worked satisfactorily, such as: the Mercalli intensity scale IMM (Modified Mercalli Intensity), widely used to characterize the damage caused by earthquakes of different intensities. Effective methodologies are available to determine the level of destructiveness of an earthquake, which are presented in this work considering the main subduction earthquakes in Chile, in addition to their directivity effects on structures located on the coastal border.

2. Characteristics of Subductive Earthquakes

In this work, the characteristics of 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. As a reference it is important to highlight the asperities of the main Chilean earthquakes have been 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 of 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 structures, Pineda and Saragoni ([1], [2], [3] and [4]) analyzed the displacement between tectonic plates that 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 the effects of seismic directivity and sliding of the non-anchored tanks.

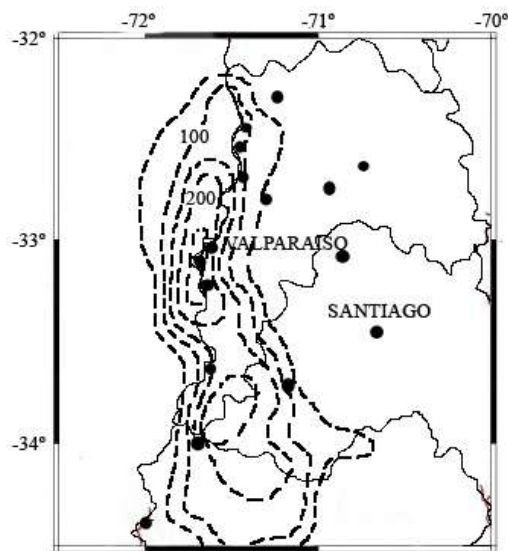


Figure 1. Chile Central 1985 earthquake, central zone. Records of two large areas with asperities edges (modified by Barrientos [5]).

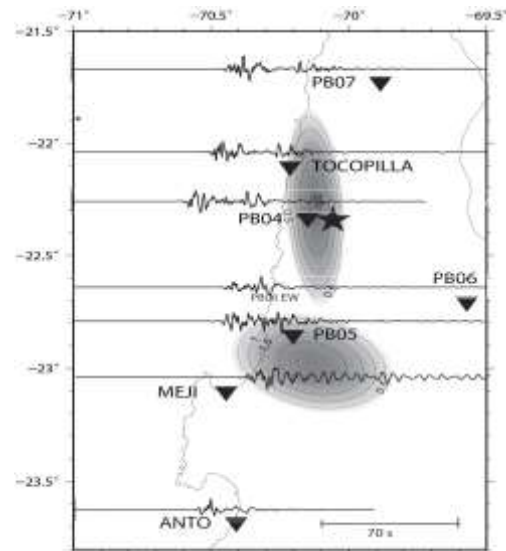


Figure 2. Tocopilla 2007 earthquake. Two asperities edges were identified near the city of Mejillones (Peyrat et al. [6])

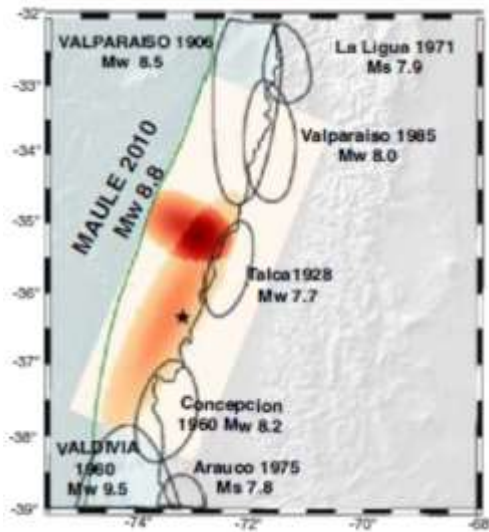


Figure 3. El Maule 2010 earthquake. Asperities located near the cities of Concepción and Constitución with 10m tectonic plate sliding (Lay et al.) [7].

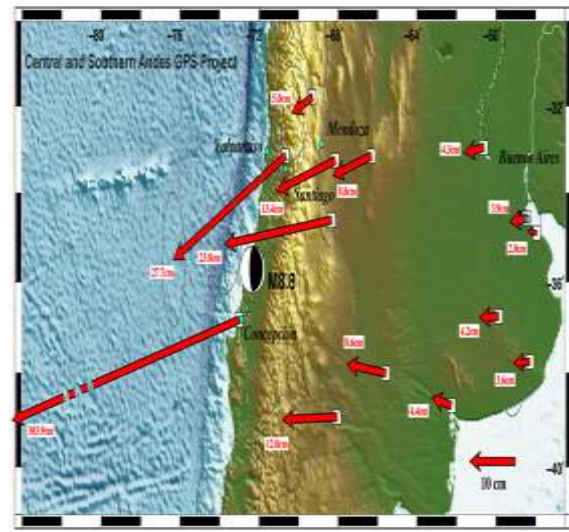


Figure 4. GPS coseismic horizontal displacement after El Maule 2010 earthquake showing 303.9 centimeters at the coast of Concepción, close to ENAP Refinery.
[https://www.soest.hawaii.edu/soest_web/soest.news_chile_feb2010_eq.htm].

3. Characterization of Seismic Movements

For a correct characterization and evaluation of earthquakes considered for the structural designs, it is necessary to have some parameters and use them in an integrated way, such as those indicated below:

3.1 Maximum Values of Records

They can be obtained from the maximum values obtained from the instrumental records or through a filtering process and integration of the original traces, this for accelerations, velocities, and relative displacements. For maximum accelerations, they can also be obtained through attenuation laws specially prepared for the areas under study, and extrapolations from areas with different seismogenic conditions are not recommended. The accelerations can be determined through the following equation:

$$x = \frac{A \cdot e^{B \cdot M}}{(R+C)^D} \quad (1)$$

Where x is maximum expected value of the seismic parameter studied, M is magnitude, R is hypocentral distance, A, B and D are constants to be determined, C is constant previously set.

3.2 Duration of Strong Movement

It is directly related to the energy that an earthquake transfers to a structure and if it can dissipate it according to its design characteristics. Among the ways to define the duration of a strong movement are considering the time elapsed between acceleration thresholds considering the accumulated time in these thresholds, considering intervals associated with percentages of sums of amplitudes squared and through the formulas proposed by Saragoni [8]:

$$\Delta t_s = \begin{cases} 2 \cdot 10^{-4} \cdot e^{1.51 \cdot M} - 2.1 \cdot 10^{-3} \cdot M(D - 60); & D \geq 60 \text{ km} \\ 2 \cdot 10^{-4} \cdot e^{1.51 \cdot M}; & D < 60 \text{ km} \end{cases} \quad (2)$$

3.3 Frequency Content

The parameters indicated have been defined in the time domain, it is also necessary to characterize the seismic records in the frequency domain. This can be done by applying the Fast Fourier Transform

(FFT) on the time series of the records. With this, it is possible to identify the predominant frequencies of the recordings and determine the response spectra.

4. Definition of Arias Tensor and Destructivity of an Earthquake

The Arias Intensity [9] is defined as a measure of the total energy accumulated in a seismic record in relation to the severity of an earthquake, considering the energy dissipated by a set of elastic linear oscillators of a degree of freedom with viscous damping, in an interval $(0, \infty)$ which is defined with the following expression:

$$I_A = \frac{\arccos(\beta)}{\sqrt{1-\beta^2}} \int_0^{t_0} [a(t)]^2 dt \quad (3)$$

Where β is the critical damping fraction, t_0 is the total duration of the record. Considering that the damping is small, can define:

$$I_A = \frac{\pi}{2g} \int_0^{t_0} [a(t)]^2 dt \quad (4)$$

In general terms the Tensor for Arias Intensity can be defined:

$$I_A = \frac{\pi}{2g} \int_0^{t_0} a_i(t) a_j(t) dt = \begin{bmatrix} I_{A11} & I_{A12} & I_{A13} \\ I_{A21} & I_{A22} & I_{A23} \\ I_{A31} & I_{A32} & I_{A33} \end{bmatrix} \quad (5)$$

Where $a_i(t)$ with $i:1,2,3$ are the time series of the accelerations recorded in each of three orthogonal components of the accelerographic station and “ g ” is the acceleration of gravity. The destructiveness capacity of an earthquake has been defined by Saragoni y Araya [10] as the quotient between the intensity of arias and the quadratic value of zero crossings per second of an accelerogram. Frequently, in design codes and seismic hazard studies, the maximum acceleration is considered as an indicator of structural damage, it is advisable to also consider the maximum expected seismic accelerations, the duration of the strong movement and the intensity of zero crossings (characteristic frequency) in the effect on the expected structural ductility demands. The destructiveness potential factor is defined from a non-stationary stochastic process of accelerations according to:

$$P_D = \frac{\pi}{2g} \frac{\int_0^{t_0} [a(t)]^2 dt}{v_0^2} \quad (6)$$

It is possible to define the destructiveness of an earthquake as the ability to generate damage to structures, which fail and eventually leave buildings and industrial facilities out of service, as well as unwanted effects on soils such as landslides, settlements, and liquefaction.

5. Characterization of Records of Subductive Chilean Earthquakes

The earthquakes analyzed in this work have the particularity of having been recorded by accelerometers, especially those of Central Chile 1985 (Figure 1), Tocopilla 2007 (Figure 2) and El Maule 2010 (Figures 3 and 4). For this reason, the results presented in this work represent the real behavior of earthquakes with respect to the amount and type of energy released, in addition to their degree of destructiveness. In particular, the Chilean earthquake of 1985 presented moderate levels of damage in the epicentral zone, despite the high values of maximum spectral accelerations in these areas. In this section, the destructive capacity of earthquakes is considered the P_D parameter defined by Saragoni and Araya [10], in relation to the Mercalli intensities indicated in figure 7. The Table 1 indicates the results obtained for the subductive earthquakes analyzed, mainly including the Arias Intensity, Destructiveness Potential and zero crossings. The importance of the records analyzed is that they allow evaluating the ductility and damage demands of subductive earthquakes, notwithstanding the foregoing, elastic response spectra are generally generated for records that do not damage structures. Table 1 indicates the cities that were analyzed with the most important subductive earthquakes recorded in Chile from 1906 in Valparaíso until the 2015 earthquake that occurred in the city of Coquimbo.

Table 1 – Arias Intensity and Destructiveness Potential of Subductive Earthquakes

City ⁽¹⁾	M _s	R	v ₀	I _A	P _D	PGA	IMM
Calama	8.8	150	12,7	8,33	51,62	0,345	7,13
Calama	8	100	13,8	11,43	59,64	0,614	7,22
Calama	8.8	150	12,7	7,65	47,42	0,253	7,07
Calama	8	100	13,8	4,18	21,82	0,497	6,57
Los Andes	8.5	162	12,0	4,88	34,09	0,352	6,86
Los Andes	8	90	14,3	4,76	23,17	1,039	6,61
Los Andes	8.5	345	11,3	1,57	12,26	0,169	6,19
Los Andes	8.5	125	12,2	6,72	45,32	0,443	7,04
Los Andes	8	82	14,8	5,47	25,08	1,203	6,66
Los Andes	8.5	326	11,4	1,73	13,39	0,180	6,25
Melipilla	8.5	143	12,1	5,70	39,16	0,393	6,95
Melipilla	8	92	14,2	4,59	22,65	0,996	6,59
Melipilla	8.5	381	11,2	1,33	10,51	0,153	6,09
Melipilla	8.5	105	13,0	11,44	67,69	0,300	7,31
Melipilla	8	106	13,6	4,50	24,46	0,450	6,64
Atacama	8.4	153	11,8	6,04	43,40	0,256	7,02
Atacama	8	100	13,8	25,79	134,60	0,294	7,75
Atacama	8.8	60	13,4	22,29	123,50	0,580	7,70
Atacama	8	120	13,0	2,27	13,50	0,340	6,26
Atacama	8.8	100	13,0	10,81	63,53	0,350	7,26
Atacama	8	91	14,3	5,38	26,38	0,490	6,69
Atacama	8	120	13,0	10,68	63,43	0,590	7,26

⁽¹⁾ City affects earthquakes considered.

Where: M_s is the magnitude of earthquake, R is hypocentral distance (km), v₀ is zero crossing (1/s), I_A is Arias Intensity (m/s), P_D is Destructiveness Potential (cm-s), PGA is Peak Ground Acceleration. Figures 5 and 6 show the correlations obtained from the main Chilean subductive earthquakes for the values of Arias Intensity and Destructiveness Potential, this for the two horizontal components of the seismic records available for each case. Figure 7 shows the distribution of a representative amount of Chilean subduction earthquake according to their destructive potential. Figure 8 shows the representative distribution of subductive Chilean earthquakes according to their predominant periods. Figure 9 shows the normalized indices of the destructiveness potential and the IMM for records of subductive earthquakes in the north and central zone of Chile, this in increasing order according to the damage generated by each one.

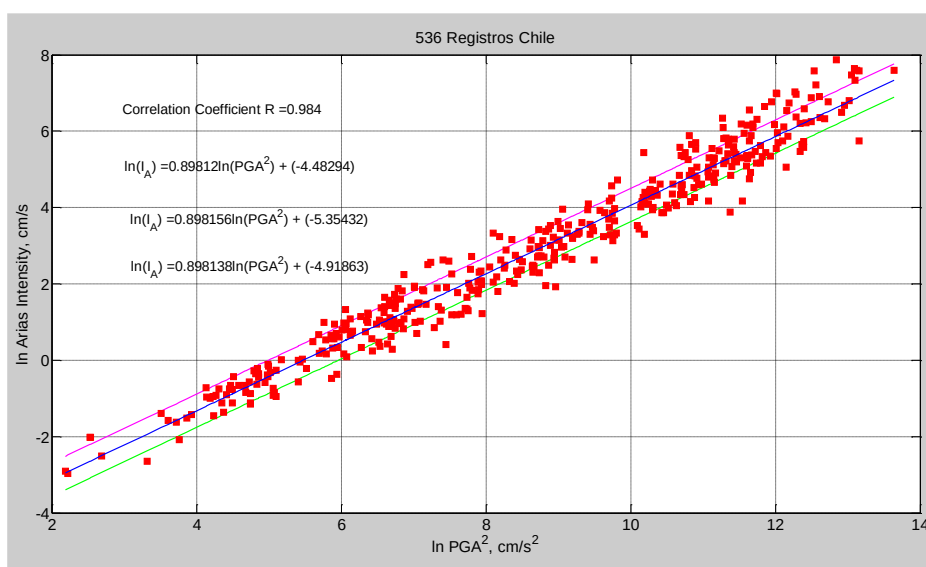


Figure 5. Arias Intensity for Subduction Earthquakes.

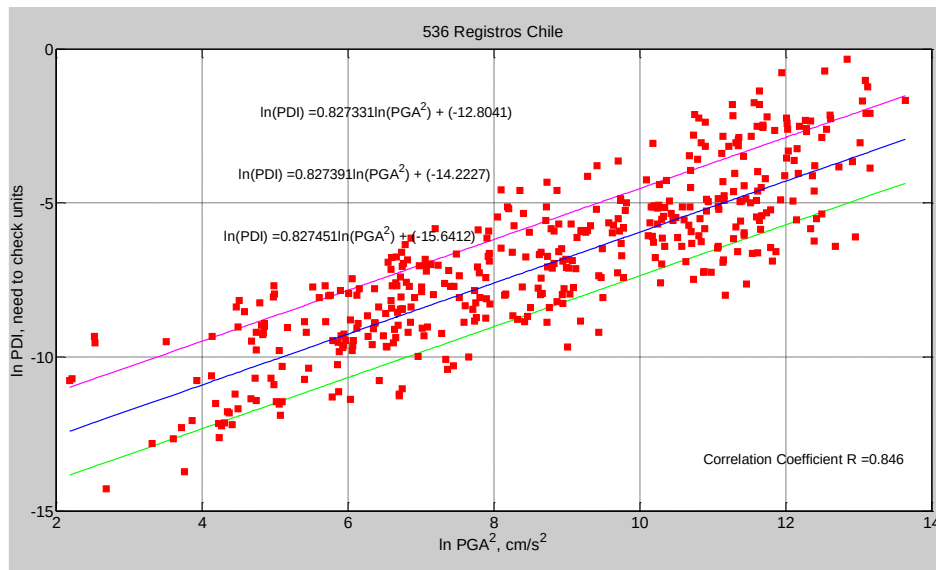


Figure 6. Destructiveness Potential for Subduction Earthquakes.

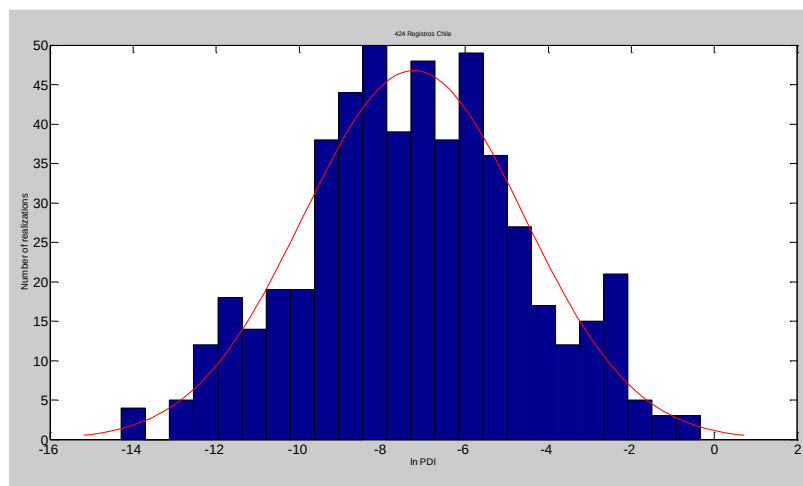


Figure 7. Distribution of Destructiveness Potential of Subductive Earthquakes.

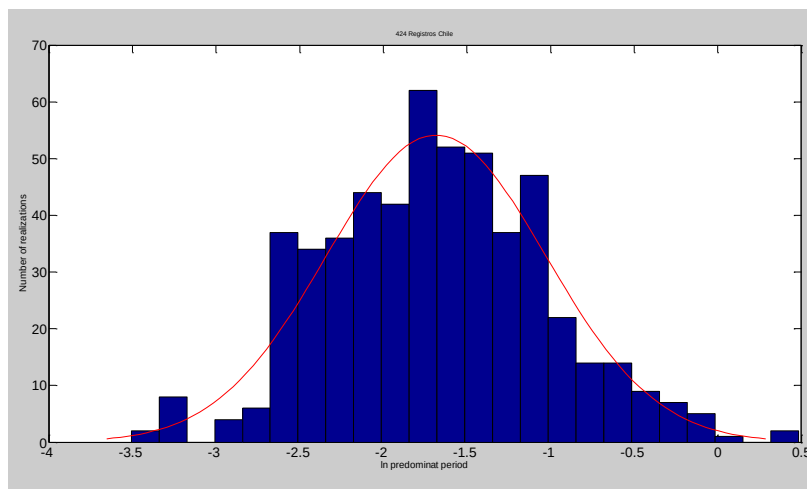


Figure 8. Distribution of Predominant Periods of Subductive Earthquakes.

The intensity scales are based on subjective appraisals of the effects of an earthquake, and can be used to measure its destructiveness, the Modified Mercalli scale (IMM) being one of the most important. Saragoni et al. [11] defined a function between the Modified Mercalli Intensity (IMM) and the destructiveness potential P_{DH} , correlating Chilean and North American earthquakes according to the following:

$$IMM = 4.56 + 1.5 \log_{10} P_{DH} \quad (7)$$

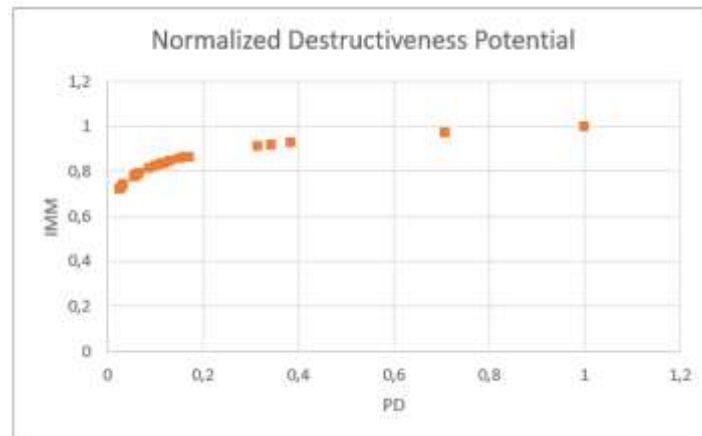


Figure 9. Destructiveness Potential as a function of IMM.

The effect of seismic directivity is incident on the seismic structural response 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 subduction Chilean earthquakes. An example to this effect has been verified in the works of Pineda and Saragoni for steel tanks located in coastal subduction zones [2] for Chile Central 1985 earthquake, then during the Tocopilla subduction earthquake in 2007 there were horizontal sliding perpendicular to the coast. The effects of seismic directivity in structures located in areas close to the asperities of the South American plate are generated by the interaction between tectonic plates, compressions are generated, releasing unidirectional coseismic displacements perpendicular to the coastal edge in a few seconds.

6. Conclusions

The destructiveness of an earthquake associated with the structural ductility requirements that can increase considerably according to duration of strong motion, depends on the expected maximum ground accelerations (PGA) and the intensity of zero crossings of a seismic record. Since subductive earthquakes tend to have high zero-crossing intensity values, accelerogram records with high PGA values can be expected, but they have not been shown to produce significant structural damage. In most design codes, maximum soil accelerations are considered for structural design, however, it has been proven that there is no direct relationship with damage to structures, since earthquakes with high accelerations do not generate significant damage. One of the relevant aspects of the subductive earthquakes in Chile in 1985 is that it had low destructiveness considering its large Richter magnitude of 7.8 and the high maximum accelerations recorded (horizontal = 0.67g and vertical = 0.85g), in addition to the high ordinate of the spectra of response in absolute accelerations. In contrary cases, it has been proven that earthquakes with low maximum accelerations can generate significant levels of structural damage, a relevant example is the 1985 Mexico earthquake. During major Chilean earthquakes (1985, 2007 and 2010), quasi-static horizontal sliding and some visible effects on structures were 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.

8. References

- [1] Pineda, P. & Saragoni, G.R., "Proposal of Seismic Coefficient and Estimate for Horizontal Sliding for Steel Tanks by Backward Seismic Analysis (BSA) Method". The 10th International Conference on the Behaviour of Steel Structures in Seismic Areas, STESSA 2021. Timisoara, Romania, 26-28 May 2021. Expositor.
- [2] Pineda, P. & Saragoni, G.R., "Tank Design Recommendations for Seismic Codes on Critical Industrial Facilities". 17th World Conference on Earthquake Engineering, 17WCEE 2021. Sendai, Japan, September 13th to 18th 2020. Expositor.
- [3] Pineda, P. & Saragoni, G.R., "Analysis of Steel Tanks in Chile Subduction Earthquakes". 16th World Conference on Earthquake Engineering, 16WCEE 2017. Santiago, Chile, January 9th to 13th 2017. Expositor.
- [4] Pineda, P., Saragoni, G.R. & E. Arze L. †, "Performance of Steel Tanks in Chile 2010 and 1985 Earthquakes". Behaviour of Steel Structures in Seismic Areas, 7th International Conference STESSA 2012. January 2012. Santiago, Chile. Expositor.
- [5] Barrientos S. 1988. Slip distribution of the 1985 Central Chile earthquake, Tectonophysics, 145, 225-241.
- [6] 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 International Journal, Volume 182, Issue 3, 1 September 2010, Pages 1411-1430.
- [7] 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.
- [8] Rodolfo Saragoni (1981): Influence of maximum acceleration, duration and frequency content on the damage caused by earthquakes. Conference pronounced at the Madrid School of Civil Engineering on January 28, 1981 and organized by the Spanish Society of Soil Mechanics and the Spanish Society of Seismic Engineering.
- [9] Arias, A., Lange G. y Arnold (1969): A measure of seismic intensity. First Peruvian Conference on Seismology and Antiseismic Engineering, Lima, Peru.
- [10] Araya, R. y Saragoni, G.R. (1984): Earthquake accelerogram destructiveness potential factor. 8th World Conference on Earthquake Engineering, San Francisco, U.S.A., August 1984.
- [11] Saragoni, G.R., Holmberg A. y Sáez A. (1989). Destructive potential and destructiveness of the 1985 Chile earthquake. V Conference of the Chilean Association of Seismology and Antiseismic Engineering, Santiago, Chile.