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SEISMIC MICROZONATION OF CONCEPCIÓN CITY

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Abstract

Chile is one of the most seismically active countries in the world, because it is located in the subduction zone generated by the convergence of the South American and Nazca plates. In this context, the city of Concepcion has been affected by destructive earthquakes and tsunamis. The last major seismic event in the region was the February 27, 2010 Mw = 8.8, Maule earthquake, which destroyed buildings of adobe and unreinforced masonry and caused damage in reinforced concrete buildings located in Concepcion, ranging from slight damage to the collapse of the Alto Rio building.

Among the factors to be studied in order to understand the variability of damages observed in Concepcion, there is the site effect, due to the city is on a basin with layers of sediment of variable thickness. Also, we must consider the location of asperities in the contact between the Nazca and South American plates, which characterized acceleration records obtained in the February 27, 2010 earthquake. In addition, in the design point of view it was observed that the response spectra of the Maule earthquake, recorded at the center of Concepcion, do not match the response spectra of the seismic design code for the area.

This work seeks to generate a seismic microzonation to better assess the seismic demand in Concepcion by performing a Probabilistic Seismic Hazard Analysis (PSHA) and using a simple methodology to include the site effect. An improved model of the 3D geometry of the interface between the plates is obtained using geophysical datasets, and hypocenters of the seismic activity in the area. The attenuation curves for rock of Abrahanson 2016 [1], Idini et al 2016 [2], Contreras- Boroschek 2015 [3] and Zaho 2006 [4], are used. Based on H/V spectra ratio for two stations in Concepción, and the response modification factors proposed by Idini [2,5], which depend on the soil period, the response spectra for accelerations and pseudo-displacements on soil, are calculated.

Seismic hazard analysis includes information on the location of the asperities. Results obtained show that their inclusion does not significantly modifies the results due to asperity closeness to the site under study. Acceleration and displacement isoseismic maps for PGA, and spectral periods of 0.3s and 1s considering 475 years return period, are obtained. It is concluded that rigid structures will have high acceleration demand in the entire Concepción, and flexible structures will have high displacement and ductility demand (above 30 cm) in areas with soil period above 0.8s. In addition, the seismic demand (acceleration and displacement) for seven buildings with more than 5 stories and demolition order after the Maule earthquake, were analyzed.

Keywords: Seismic Hazard , Concepción, Site Effects

1. Introduction

Chile is one of the most seismically active countries in the world, because it is located in the subduction zone generated by the convergence of the South American and Nazca plates.

In the initial city of Concepción, the level of destruction caused by a major seismic event in 1751, led to the relocation of the city from Penco Valley to Mocha Valley. In this new location of the city, the last major seismic event experimented was the February 27, 2010 Mw = 8.8, Maule earthquake, which destroyed buildings of adobe and unreinforced masonry and caused damage in reinforced concrete buildings, ranging from slight damage to the collapse of the Alto Rio building. The characteristics of the failures observed during the Maule earthquake in 2010 were not observed during Central Chile earthquake in 1985, because of that the seismic design standards for the buildings affected by Maule earthquake do not include requirement of ductility and confinement of the boundary zone in walls.

The failures observed in the country, and on areas with high predominant period of the soil or site effects, like in Concepción, make it necessary to modify design standards, such as confinement requirements, soil classification, acceleration and displacement response spectrums, some of these have been addressed Decree 60 and 61 [6].

In order to contribute to the solution of these questions or modifications, seismic demand in Concepcion are calculated by generating a seismic microzonation of the city area by performing a Probabilistic Seismic Hazard Analysis (PSHA) for rock and later, through response modification factors depending on the soil period and level of amplification, the response spectrum on soil are obtained. The results obtained allow to estimate the expected acceleration and displacement demands in a group of seven buildings, which had severe damage during the Maule earthquake.

There is a variety of studies that have calculated seismic hazard for Chile, the most recent ones are Leyton 2009 [7] and Nuñez 2015 [8]. These studies presented PGA values (the former) and rock and soil response spectra (the latter). However, they do not include the soil particular characteristics, such as amplification effects or predominant period of the soil. In addition, the effect of asperities on the probabilistic seismic hazard is also studied. Surface faults effect could be analyzed in future studies.

2. Methodology

The Probabilistic Seismic Hazard analysis is performed in the area between latitudes 36.835S and 36.808S and longitudes 73.072W and 73.036W. For soil characterization, we have 87 sites' periods and Vs30 data, both were obtained from Montalva et al [9]. Vs30 is calculated for each one of the 87 sites according to the interpolation carried out. When comparing isoseismic charts period and Vs30 for the soil, it was not observed a correlation. Furthermore, an almost constant Vs30 value is globally observed (Fig. 1).

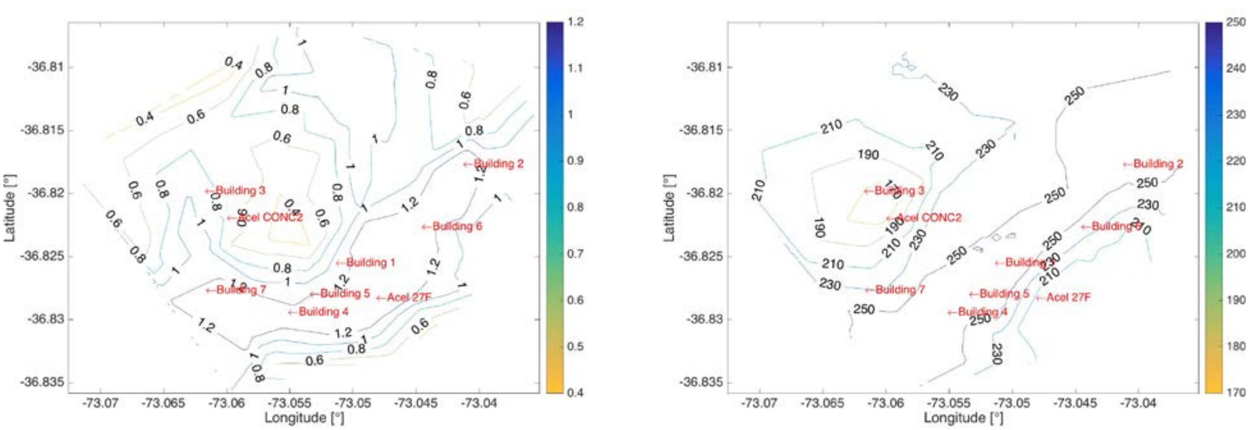

Fig. 1 – Period Isoseismics [s] and Soil VS30 [m/s]

2.1 Geometry of the interface in the subduction zone

A 3D geometry is constructed to represent the plate interface, defining the interplate and medium-depth intraplate seismic source. The geometry is constrained by earthquake hypocenter catalogs of relocated seismicity [10,11] seismic profiles [12,13,14] , seafloor bathymetry and topography from ETOPO02 and previously obtained models for Nazca plate [15,16,17] The 3D surface is discretized using triangular elements (Fig. 2). Seismic hazard results were compared using three levels of mesh refininement, with the triangle average areas for each level of: 360 km^2, 90Km^2, 22.5 km^2. However, no major differences were observed on results, thus, futher work is carried out using the coarser mesh.

2.2 Asperities Location

In order to study asperities influence in probabilistic seismic hazard, two alternatives are used.
First: The effect of considering the position and dimensions of asperities, as defined by Idini [2] is studied. Geometry and location data for this first approach are shown in Table 1.

Table 1 – Asperities Geometry and Position, Alternative 1

Asperities	**Lower Left Corner Coordinates** Lat [°], Lon [°]	**Length and Width** [km] , [km]	**Strike and Dip** [°], [°]
1	35.35S, 73.25W	155, 85	19,18
2	36.30S, 73.55W	50, 45	19,18
3	37.75S, 74.05W	100, 45	19,18

Data obtained of [2]

Second: The effect using the asperities defined by Ruiz [18] (Location of asperities considering long-period waves). This asperities location (Table 2) is within asperities 1 and 2 defined by Idini [2]. Therefore, as a second alternative, only asperities 1 and 2 defined by Idini are considered for simplicity.

Table 2 – Location of Roughness Defined by Ruiz

Roughness	**Location** Lat [°], Lon [°]
1	35.8S, 72.9W
2	34.9S, 72.5W

Data obtained of [18]

In order to model asperities, the source surface triangles within each asperities defined in Table 1 are calculate. See Fig. 2. For each case, these elements (asperities) are assigned a seismic occurrence probability of 80% of the total inter-place source for Mw higher than a 8.2.

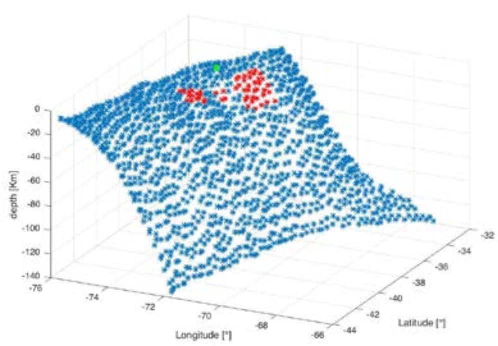

Fig. 2 – Surface that Defines the Source and Roughness Considered.

2.3 Gutenberg Richter Curves

The Gutenberg Richter curves proposed by Nuñez [8] were used, which are based on the zones identified by Susa [19] and calculated using the maximum verisimilitude method. Our study considered zones 6, 7, and 8, located between 47º and 31.7º latitude south. Adding other zones do not affect significantly the results. There is also the option to use Leyton [7] curves, based on zones identified by Martin [20]. However, the latter option was discarded because it is expressed in terms of Ms and a transformation from Ms to Mw was required.

2.4 Attenuation Formulas

Attenuation formulas used to calculate acceleration response spectrum for Rock are: Abrahanson 2016 [1], Idini et al 2016 [2], Contreras- Boroschek 2015 [3], and Zaho 2006 [4] (See Fig. 3). The logic tree weights used in the PSHA are indicated in Table 3.

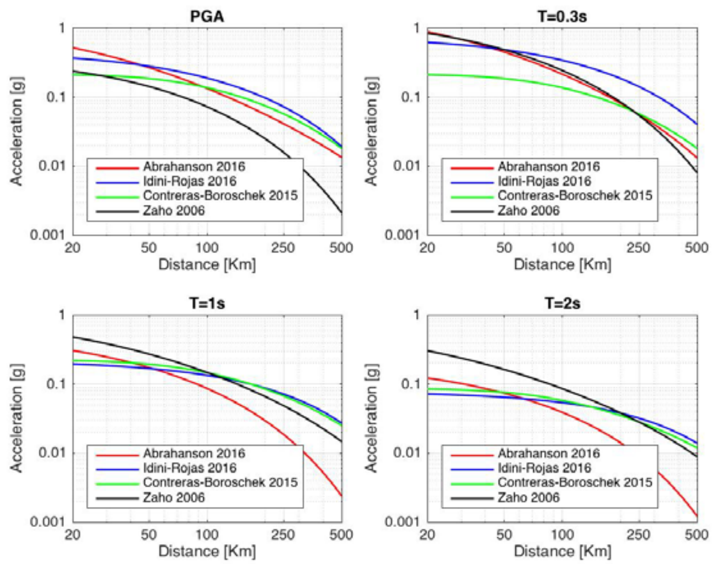

Fig. 3 – Attenuation Formulas Used (Interplate, Mw=8.5, Hipocenter Depth=30Km)

Table 3 – Weights in the Logical Tree for each Attenuation Formula

Attenuation Formulas	Factor
Abrahanson 2016	0.20
Idini – Rojas 2016	0.35
Contreras- Boroschek 2015	0.25
Zaho 2006	0.20

2.5 Soil Modification Response Factor

In order to calculate acceleration response spectra for soil, soil modification factor f_s (T), calculated by Idini [2,5], is used. This factor amplify the response spectrum for rock at each period to obtained the response spectrum for soil. In Concepción, Idini calculates H/V ratio of two sites, corresponding to accelerographs, identified in Fig. 1, as Acel 27F (CONC) and CONC2. According to his classification, CONC has H/V a peak of 6, which indicate a pick of amplification (f_s) equal to 4.29. Meanwhile, CONC2 has H/V peak of 4, which indicate a pick of amplification (f_s) equal to 2,85. See Fig. 4

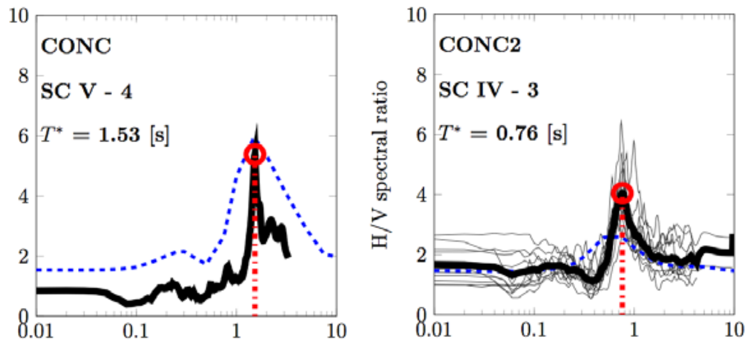

Fig.4 – H/V ratio of acceleration response spectra with 5% damping for CONC (Acel 27F) and CONC2 stations. (Fig. B5 of [2])

Using the amplification factor calculated for the two station, and the soil factor (S(To)) for each of the type soil defined by Idini [2,5], the soil modification response factor used in this work are presented in Fig. 5.

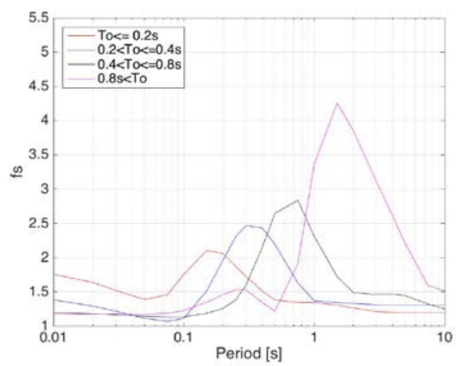

Fig 5. Soil modification response factor: 10^Fs

2.6 Implementation of Probabilistic Seismic Hazard analysis

The Probabilistic Seismic Hazard has been determined for a return period of 475 years using the methodology presented by Baker 2008 [21] and Abrahamson 2010 [22]. Using the indicated information for Concepcion (3D suface, Gutenberg Richter Curves, Attenuation Formulas) the rock acceleration response spectra (S_a) is obtained. Later, multiplying the response spectrum obtained from the PSHA by the soil modification response factor presented before, the soil acceleration response spectre are obtained. The displacement pseudo spectra are calculated using the well-known relation: $PS_D = S_a \cdot T^2/4\pi^2$

3. Results of PSHA

Using the methodology described above is determined the effects of asperities on probabilistic seismic hazard: In both asperities configurations (Table1, Table 2), in the asperities' region is assigned 80% of interplate seismic occurrence probability for Mw higher than 8.0. The response spectrum for rock are calculated for site 31. When analyzing disaggregation charts, a higher contribution from interplate events is observed between Mw 8.5 and 9 (Fig. 6), compared to observations in the case of no asperities information included, with an approximately constant contribution between Mw 8.0 and 9.5 (see Fig. 8). However, comparing results, an increase in spectral ordinates of 2% is only observed.

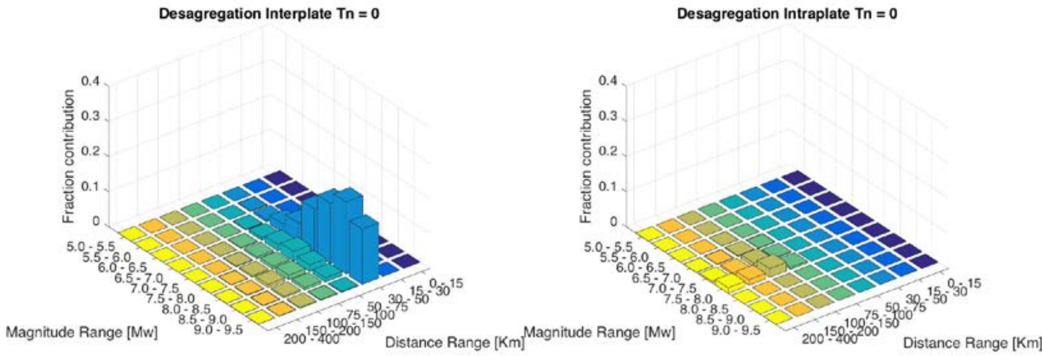

Fig. 6 – Disaggregation on Rock for PGA including Asperities Effect.

Based on the results mentioned before, it has been decided not to include the influence of asperities on the rest of the studio. The uniform hazard analysis (UHS) is generated on rock. Results for site 31 are shown, used as representative for the entire Concepción, because the distance from the source is quite similar for the 87 sites analyzed. Following, acceleration response spectra are shown for return period of 475 years (Fig. 7), and disaggregation charts for PGA (Fig. 8).

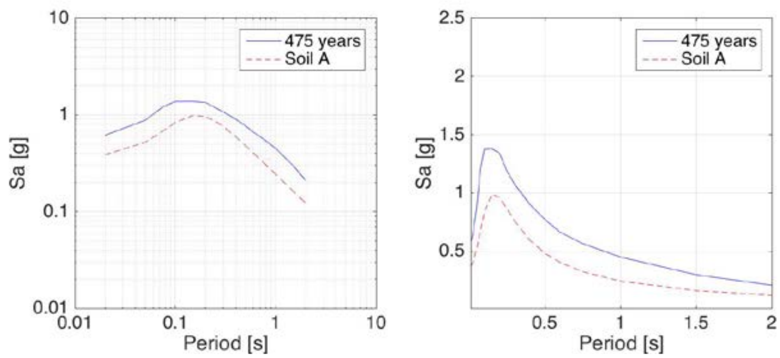

Fig. 7 – Acceleration Spectra (S_a) on Rock for 475 Years Return Periods, Spectra soil A (NCh433-DS 61)

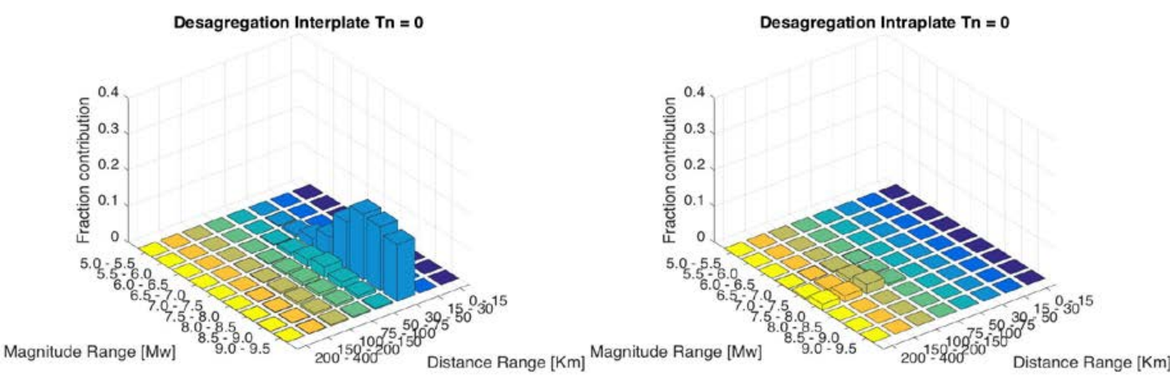

Fig. 8 – Disaggregation on Rock for PGA

For soil, representative results from site 12 (this site is close to the accelerograph CONC2), To=0.7 s, Vs30= 160 m/s, located at latitude -36.8214 longitude -73.0599, and from site 31(this site is close to the accelerograph that recorded the 27F event), To=1.4 s, Vs30= 255 m/s, located at latitude -36.8266 longitude -73.0468 are shown. Following, acceleration and displacement response spectra for return period of 475 years are presented (Fig. 9, Fig. 10 for site 12; Fig. 11, Fig. 12 for site 31)

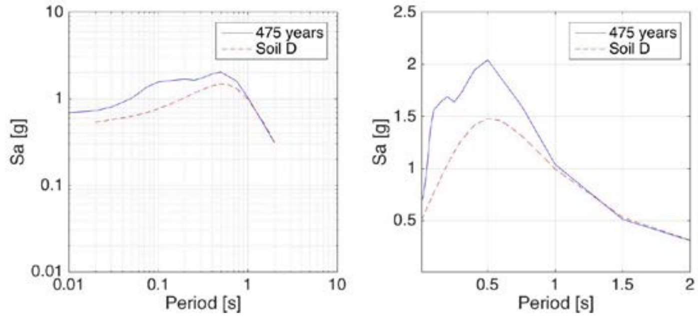

Fig. 9 – Acceleration Spectra on Soil, Site 12, To=0.7s, 475 Years return Periods, and Soil Spectrum D (NCh433-DS 61)

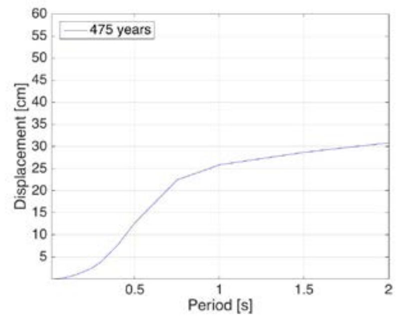

Fig. 10 – Displacement Pseudospectra on Soil (PS_D), Site 12, To=0.7s, 475 Years Return Periods

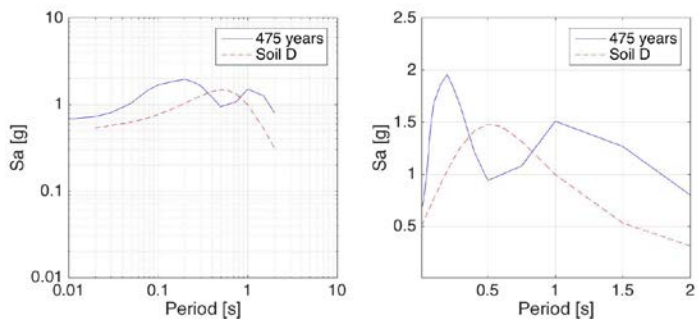

Fig. 11 –Acceleration Spectra on Soil, Site 31, To=1.4s, 475 Years Return Periods, and Soil Spectrum D (NCh433-DS61)

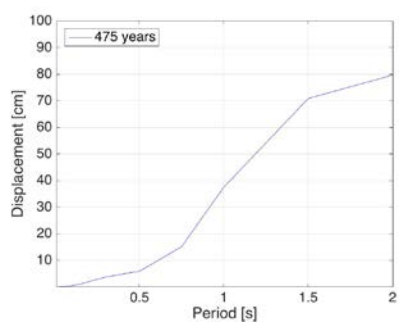

Fig. 12 – Displacement Pseudospectra (PS_D) on Soil, Site 31, To=1.4s, 475 Years Return Periods

Following, acceleration and displacement isoseismic are shown for a 475 years return period for PGA and spectral period of 1s (Fig 13, Fig. 14, Fig. 15), and acceleration isoseismic for spectral period of 0.3 s, Fig. 16 (expected displacement spectral periods for a 0.3 s spectral period are of 4 cm).

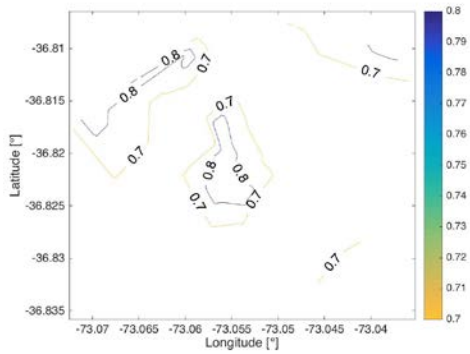

Fig. 13 PGA Isoseismic

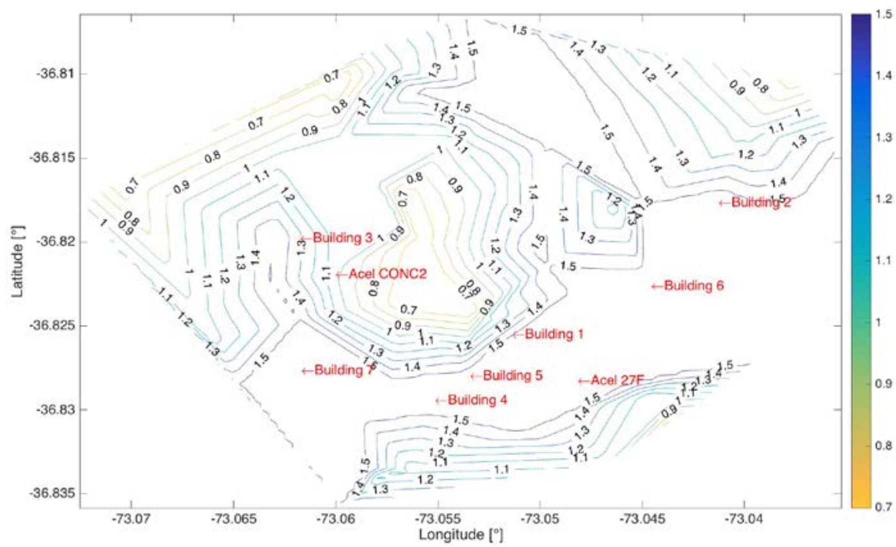

Fig. 14 – Spectral acceleration Isoseismic (S_a [g]) for Spectral Period of 1s

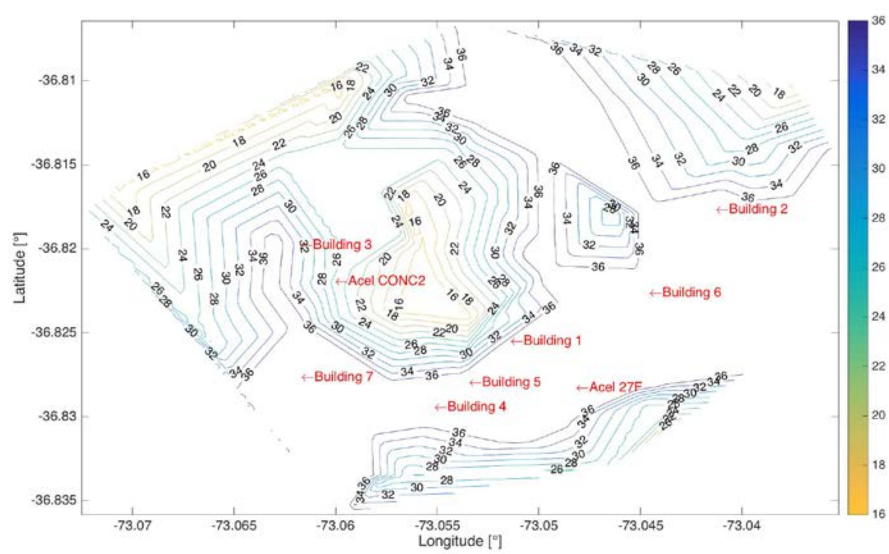

Fig. 15 – Pseudospectra Displacement Isoseismic (PS_D [cm]) for Spectral Period of 1s

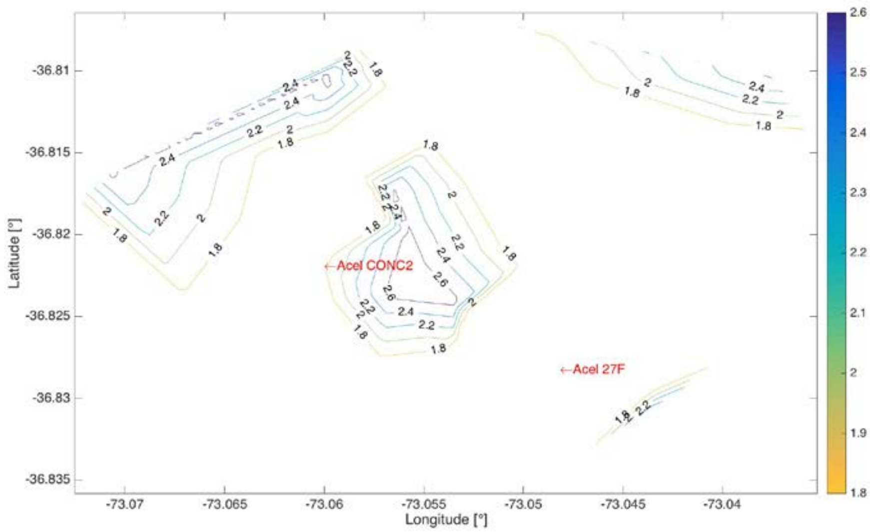

Fig. 16 – Spectral acceleration Isoseismic for Spectral Period of 0.3s

In order to compare the results obtained with the acceleration spectra from the Maule earthquake, the following is graphics are shown:
(a): The acceleration response spectra for Concepción (damping 5%) based on the event records during the 27F.
(b): The uniform probability response acceleration spectra calculated for return period of 475 years, using $f_S(T)$ for site 31, located at latitude -36.8266, longitude -73.0468, To=1.4 s. This site is selected because it is close to recorded event during the 27F.
(c): Acceleration response spectra using the attenuation formulas of Idini et. Mw=8.8, To=1.4, n = 1.89, H=25Km, R=30 Km.

It is observed that the response spectra of the Maule earthquake is lower than the uniform hazard spectrum obtained from the PSHA.

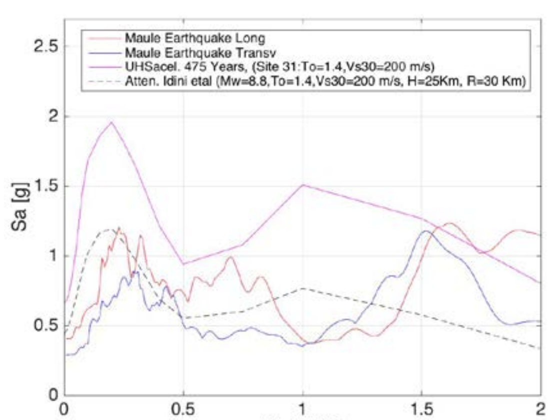

Fig. 17 – Maule Earthquake Response Spectrum (Concepción centro), UHS acceleration, Attenuation Idini et al for To=1.4, Vs30=200 m/s, H=25 Km, R=30 Km, Mw=8.8

Demand on Concepción Buildings

In order to study the acceleration and displacement demand expected in buildings from the probabilistic hazard analysis, a sample of 7 buildings with more than 5 stores with total or partial demolition order due to the Maule Earthquake, are selected. Their identification number is shown in Fig. 18.

Fig. 18 – High Buildings Studied [23]

Natural vibration periods (**T**$_n$) for buildings 2 to 7 were obtained from Westenenk et al [23]. Periods for buildings 1 and 7 were estimated (Approximate period according: number of floors/20 [s]). Based on the Probabilistic Seismic Hazard analysis for a return period of 475 years, the acceleration and pseudo-displacement demand for each building fissured period is obtained ($T_{fissured}$ = 1.5$T_{natural}$ defined on [6]). The last displacement (δu=1.3PS_D ($T_{fissured}$) [6]) is defined and based on these results, drift for each building is calculated and presented in Table 5. In order to illustrate the acceleration demand on the studied buildings, their location in the spectral accelerations and displacements for a spectral period of 1 s, for a return period of 475 years, are shown in Fig. 14 and Fig. 15.

Table 4 – Building Properties: Geographic Coordinates, Natural Vibration Periods (**T**$_n$) and Soil Properties

Building	**Latitude [°]**	**Longitude [°]**	**Stories**	**T$_n$ x [s]**	**T$_n$ y [s]**	**T$_n$ z [s]**	**To soil [s]**	**Vs30 [m/s)**
1	36.8255S	73.0514W	9+0	-	0.45 (*)	-	1.05	250
2	36.8177S	73.0413W	20+1	0.62	0.71	0.58	1.25	260
3	36.8198S	73.0618W	12+0	0.5	0.33	0.39	0.9	170
4	36.8294S	73.0552W	21+2	0.93	0.53	0.28	1.25	260
5	36.8280S	73.0535W	17+1	0.61	0.77	0.88	1.15	260
6	36.8226S	73.0446W	18+1	0.56	0.8	0.68	1.3	240
7	36.8277S	73.0617W	15+2	-	0.75 (*)	-	1.2	230

Periods **T**$_n$ x, **T**$_n$ y, **T**$_n$ z were obtained from [23], (*) Approximate period according: number of floors/20

Table 5 – Dynamic properties and spectral demand of the analyzed buildings

Building	$T_{fissured}$ x **[s]**	$T_{fissured}$ y **[s]**	$S_a(T_{fis})$**x [g]**	$S_a(T_{fis})$**y [g]**	**SD(**T_{fis}**)x [cm]**	**SD(**T_{fis}**)y cmg]**	δu **x [cm]**	δu **y [cm]**	Drift
1	-	0.59	-	0.99	-	9.17	-	11.9	0.0053
2	0.93	1.07	1.39	1.48	31.2	42.2	40.56	54.9	0.0104
3	0.75	0.5	1.08	0.94	15.1	5.8	19.63	7.5	0.0065
4	1.4	0.8	1.32	1.17	64.2	19.6	83.46	25.5	0.0145
5	0.92	1.16	1.37	1.43	30.3	48.2	39.39	62.7	0.0139
6	0.84	1.2	1.23	1.41	23.1	50.8	30.03	66.0	0.0139
7	-	1.13	-	1.45	-	46.2	-	60.1	0.0141

$T_{fissured}$ = 1.5$T_{natural}$ defined on [6]; δu=1.3PS_D ($T_{fissured}$) defined on [6];Drift= max(δux,δuy**)** / Nº Stories•250 [cm]

4. Conclusions

In this work, was presented the seismic microzonation for Concepcion city. This was based on the acceleration response spectrum for rock calculated using a PSHA and later using soil modification response factors, which allow calculating spectral accelerations and displacements to occur on soil in the city of Concepción.

According to observations, Vs30 by itself is not a good parameter for soil classification. Use of *To soil* period is recommended as an additional parameter.

With regard to asperities inclusion in Concepción probabilistic seismic hazard, it is noted that, due to their closeness to the studied site and to the use of attenuation formulas using distance to the rupture, no significant seismic hazard increase is observed when the probability occurrence of events increase at asperities for Mw>8.2. However, for Chile zones where the studied site is at a longer distance from asperities, seismic hazard is expected to decrease when the probability occurrence of events increase at asperities. For this reason, not considering this higher probability would imply, in these cases, an overestimation of probabilistic seismic hazard.

The disaggregation chart in Fig. 8 shows that the larger contribution is from interplate events, which concentrates in the range between Mw 8 and 9.5, with a hypocenter distance between 30 and 50 Km. As it could be expected, these values are higher than those of the design spectrum for soil A (rock, Vs30 >900 m/s), but of similar form. It is herein ratified that the contribution of medium-depth intraplate events is not significative.

Acceleration response spectra for sites 12 and 31 obtained from the microzonification have a quite different behavior, however, both will be classified as soil D, according to the current seismic design standard (180m/s ≤ Vs30 < 350m/s) [6,24]. For a return period of 475 years: For site 12 (Fig. 9) with To=0.7, a pick is observed for 0.5s spectral period, which exceeds 2 g. For site 31 (Fig.11) with To = 1.4 s, 2 picks are presented; the first one exceeds 1.9 g for spectral periods of less than 0.2 s, and the second pick exceeds 1.5 g for the spectral period of 1s. This behavior is similar to that observed in the response spectrum of Maule earthquake for Central Concepción.

In displacements for site 12 (Fig. 10) (To=0.7), 25.8 cm are reached for a spectral period of 1s. For site 31 (Fig. 12) (To=1.4 s), 37.5 cm are reached for a spectral period of 1s, which exceeds 70 cm for longer spectral periods.

From acceleration (Fig. 14, Fig. 16) and displacement (Fig. 15) isoseismic maps for spectral periods of 0.3s and 1s, with 475 years return period, it is concluded that:

- Rigid structures will have a high spectral acceleration demand in the entire Concepción (above 1.6g)
- Flexible structures will have a high displacement and ductility demand (above 30 cm) in zones with soil periods above 0.8 s, which may reach more than 70 cm for spectral periods longer than 1.5s.

The above coincides with the fact that five of seven buildings of more than 5 stories and demolition order after the Maule earthquake are in the last case. For a 475 years return period a higher spectral acceleration demands expected for all the studied buildings exceed 0.9 g, and reach 1.48 g for building number 2. In 4 of the 7 building the last displacement was more than 60 cm, which implies a drift higher than 1.3%.

We conclude that this work provides an accurate and simple methodology to calculate the acceleration and displacement demand levels in the city of Concepción, which could be applied to other cities with site effects associated to soil, and to be considered in the design standards.

5. Acknowledgements

We are thankful for the collaboration of Profesor Gonzalo Montalva and its support providing the soil period data in the area of Concepción.

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6. References

[1] Abrahamson N, Gregor N, Addo K, BC Hydro Ground Motion Prediction Equations for Subduction Earthquakes, Earthquake Spectra, February 2016.

[2] Idini B, Curvas de atenuación para Terremotos Intraplaca e Interplaca en la zona de Subducción Chilena, Memoria para optar al título de Ingeniero Civil, Universidad de Chile, 2016.

[3] Contreras V, Boroschek R, Curvas de Atenuación Espectrales para Sismos Chilenos , XI Congreso Chileno de Sismología e Ingeniería Sísmica ACHISINA 2015.

[4] Zhao J, Zhang J, Asano A, Ohno Y, Oouchi T , Takahashi T, Ogawa H, Irikura K, Thio H, Somerville P, Fukushima Y, Fukushima Y, Attenuation relations of strong ground motion in Japan using site classification based on predominant period. Bulletin of the Seismological Society of America.

[5] Idini B, Rojas F, Ruiz S, Pastén C, Leyton F, Empirical dynamic amplification factors for sites based on seismic noise, 2016.

[6] Ministerio de Vivienda y Urbanismo Gobierno de Chile, Decree 60 and 61 Diseño Sísmico de Edificios, 2011.

[7] Leyton F, Ruiz S,Sepúlveda S, Preliminary re-evaluation of probabilistic seismic hazard assessment in Chile: from Arica to Taitao Peninsula, Adv. Geosci., 147-153, 2009.

[8] Núñez, I. Nuevo Peligro Sísmico para Chile, Memoria para optar al título de Ingeniero Civil, Universidad de Chile, 2014.

[9] Montalva G, Chávez-Garcia F, Tassara A, Jara D, Site Effects and Building Damage Characterization in Concepción after the Mw 8.8 Maule Earthquake, Earthquake Spectra, Ocober 2015.

[10] Engdahl, E. R., and A. Villaseñor (2002), Global seismicity: 1900–1999, pp. 665–690, International Handbook of Earthquake and Engineering Seismology.

[11] Engdahl, E. R., R. van der Hilst, and R. Buland (1998), Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, Bulletin of the Seismological Society of America, 88(3), 722–743.

[12] F3 - Kolja Groß, Stefan Buske, Serge A. Shapiro, Peter Wigger, & the TIPTEQ Research Group, Seismics Team* (2008), Reflection seismic imaging of the Chilean subduction zone around the 1960 Valdivia earthquake hypocenter. 7th International Symposium on Andean Geodynamics (ISAG 2008) Nice, France. (Extended Abstracts pp 245-248).

[13] Christof Sick · Mi-Kyung Yoon · Klaus Rauch · Stefan Buske · Stefan Lüth · Manuel Araneda · Klaus Bataille Guillermo Chong.

[14] Charlotte M. Krawczyk · James Mechie · Stefan Lüth · Zuzana Tašárová · Peter Wigger · Manfred Stiller · Heinrich Brasse Helmut P. Echtler · Manuel Araneda · Klaus Bataille.

[15] Tassara, A., H. J. Götze, S. Schmidt, and R. Hackney (2006), Three?dimensional density model of the Nazca plate and the Andean continental margin, *Journal of Geophysical Research: Solid Earth (1978–2012)*, *111*(B9).

[16] Hayes, G. P., and D. J. Wald (2009), Developing framework to constrain the geometry of the seismic rupture plane on subduction interfaces a priori–a probabilistic approach, *Geophysical Journal International*, *176*(3), 951–964.

[17] Hayes, G. P., D. J. Wald, and K. Keranen (2009), Advancing techniques to constrain the geome- try of the seismic rupture plane on subduction interfaces a priori: Higher?order functional fits, *Geochemistry Geophysics Geosystems*, *10*(9).

[18] Ruiz S, Madariaga R, Astroza M, Saragoni R, Lancieri M, Vigny C, Campos J, Short-Period Rupture Process of the 2010 Mw 8.8 Maule Earthquake in Chile.

[19] Susa D, “Evaluación del Peligro Sísmico Asociado a sismos de tipo interplaca en Chile y Sur del Perú utilizando distribución bi-paramétrica de Weibull. ”. Memoria para optar al título de Ingeniero Civil, Universidad de Chile, 2004.

[20] Martin A, “Hacia una nueva regionalización y cálculo del peligro sísmico en Chile, Memoria para optar al título de Ingeniero Civil, Universidad de Chile, 1990.

[21] Baker J, An Introduction to Probabilistic Seismic Hazard Analysis (PSHA), Version 1.3, October 2008.

[22] Abrahamson N, Seismic Hazard Analysis and Design Ground Motions, Department of Civil and Environmental Engineerin UCSD, Spring 2010.

[23] Westenenk B, De la Llera J, Besa J, Jünemann R, Moehle J, Lüders C, Inaudi J, Elwood K, Hwang S, Response of Reinforced Concrete Buildings in Concepción during the Maule Earthquake, Earthquake Spectra, Volume 28.

[24] Instituto Nacional de Normalización (INN – Chile), NCh 433Of96 Diseño Sísmico de Edificios 1996.