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OBSERVATION OF SEISMIC AMPLIFICATION ON SUBDUCTIVE ENVIRONMENT

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ABSTRACT

Damages caused by earthquakes are strongly dependent on local site conditions and seismic source. Accordingly, site conditions and earthquake characteristics seem to be the main factors that control the seismic response acting in a particular place. To investigate these factors at different soil conditions in the Santiago basin (Chile), four seismic stations (accelerometers) have been installed which have recorded more than 40 seismic events with magnitudes in the range of 4.2 to 6.0. It is important to mention that Santiago basin is somewhat unique since it is located in a subduction zone environment with a high seismic activity, where earthquakes come from at least three different seismic sources. Ambient vibrations and seismic events recorded at the ground surface have been used to compute the H/V spectral ratios, and the results indicate a good correlation between both types of measurements at low frequencies. Using spectrograms, the analysis of the frequency content along the recorded earthquakes was performed. The results indicate that depending on the type of earthquake, the main frequency obtained by H/V spectral ratio show up as the main frequency of the horizontal acceleration records. These results confirm that both site conditions and type of earthquake have to be considered in the ground motion that take place at the ground surface.

Keywords: Site effect, H/V spectral ratio, seismic amplification.

INTRODUCTION

Chile is located to the south-west of the American Continent in a subductive seismic environment that is associated with the subduction of Nazca plate under South America plate. As a result of this tectonic collision, Chile presents one of the highest rate of seismicity of the world and so far the larger ever recorded ground motion (1960 Valdivia earthquake with M=9.5, Madariaga, 1998).

Santiago, capital city of Chile, is located approximately at latitude 33°27'S and longitude 70°40'W, nearly 100 km inland from the Pacific Ocean. Since the Spanish arrival and written information is available, the sequence of large seismic events that have hit the central part of Chile located between latitudes 32º S and 34.5º S has been exposed to a notable periodicity. The years of occurrence of these major events have been reported as follows: 1575, 1647, 1730, 1822, 1906 and 1985, resulting in an average recurrence interval of 82 years (Comte et al. 1986). The observed damages caused by these earthquakes confirm the strong effect of the local conditions that have been reported by other researchers as Borcherdt, 1970 and 2002.

On the other hand, Santiago holds the main concentration of infrastructure and economic activity, with a metropolitan area that has a population close to 5.5 millions that corresponds to more than one third of the total population of Chile. Considering the high seismic hazard that affect Santiago in

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conjunction with the political importance of this city, an attempt to characterize the seismic response of Santiago basin has been carried out. Accordingly, H/V spectral ratio measurements and seismic records obtained in different areas of the basin have been analyzed and parts of these results are presented in this article.

GEOLOGY AND GEOTECHNICAL CHARACTERIZATION

From a geological point of view, Chile to the south of parallel 33º is characterized by the existence of three morphostructural units running parallel to each other with a north-south orientation. From east to west, these units are the Andes Mountain Range, the Central Valley and the Coastal Mountain Range. This configuration probably originated during the maximum compression stage that took place during the Oligocene – Pliocene epochs (Thiele, 1980). The Andes Mountain Range consists of volcanic and sedimentary rocks, intrusive bodies, volcanic materials and active volcanoes. The general shape of this basin is presented in Fig. 1 with two profiles where the types of soils are indicated.

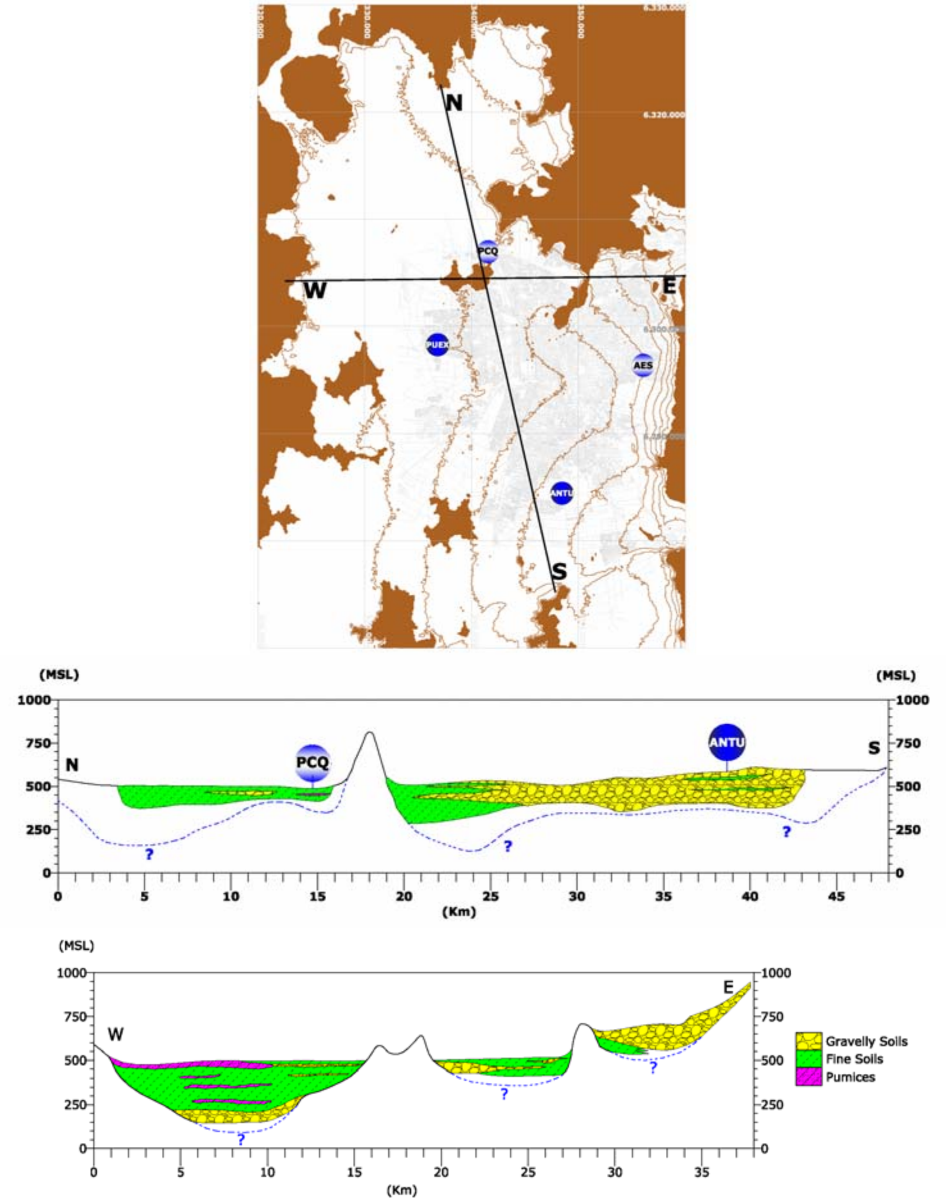


Fig. 1. Seismic stations located in Santiago basin and geological profiles.

Santiago basin is filled mainly by alluvial sediments and by a much lesser degree by materials associated with volcanic activity as pumices (Valenzuela, 1978). Gravelly soils have been deposited by the Mapocho and Maipo rivers and present high strength and high stiffness associated with shear wave velocities typically around 800 m/s (Acevedo, 1973). The pumices also present good geotechnical properties with shear wave velocities in the rage of 400 to 600 m/s (Lagos, 2003). The fines materials found in the north part of the basin consist of clayey and silty soils of low plasticity with shear wave velocities estimated in the range of 250 to 400 m/s.

RECORDED SEISMIC EVENTS

The Chilean Seismological Service of University of Chile (SSN) and the Department of Structural Engineering of the Catholic University of Chile (CU) have seismic instrumental networks monitoring the soil deposits in Santiago basin, which general features are indicated in Table 1 and the location of the seismic stations are shown in Fig. 1.

Table 1. Seismic Stations located in Santiago basin

Station name	Abbreviation	Latitude (º)	Longitude (º)	Sensor	Institution
Antumapu	ANTU	-33.569	-70.634	EpiSensor, FBA ES-T	SSN
Liceo Pudahuel	PUEX	-33.441	-70.758	FBA-23	SSN
Planta Cervecera Quilicura	PCQ	-33.364	-70.702	SMAC-MD-I	CU
Aeródromo Eulogio Sánchez	AES	-33.459	-70.548	SSA-1-I	CU

In this study, earthquakes of magnitude greater than 4.5 and which epicenters are located in the area given by 32,0ºS to 34,5ºS and 69,5ºW to 73,0ºW have been used. The date, time, location, depth, magnitude and type of earthquakes are indicated in Table 2 and 3 for seismic events registered by SSN and CU stations, respectively.

On the other hand, the locations of the hypocenters of each recorded earthquake are shown in Fig. 2.

It has been established that the coupled zone between the Nazca and South America plates in central Chile, where the interplate earthquakes are expected to take place, is developed up to a depth of 55 km (Tichelaar and Ruff, 1993; Madariaga, 1998). Accordingly, the earthquakes in this area can be classified depending on the depth of their hypocenter; Interplate (shallower than 55 km in the contact zone), Intraplate (deeper than 55 km) and cortical or shallow (in the South American plate).

Table 2. Earthquakes recorded by SSN stations since 2002 to 2005

Event	Date	Local time	Latitude (º)	Longitude (º)	Depth (km)	Magnitude	Type of earthquake
1	01/10/2005	13:24	-33.908	-70.447	118.5	4.5	Intraplate
2	12/08/2005	08:59	-33.462	-70.676	88.0	4.7	Intraplate
3	13/04/2005	09:25	-33.14	-72.925	24.7	5.2	Outer-rise
4	29/03/2005	16:38	-33.711	-72.277	34.0	5.0	Interplate
5	29/10/2004	00:03	-32.475	-71.755	28.0	4.2	Interplate
6	29/10/2004	00:00	-33.922	-72.562	29.0	4.8	Interplate
7	29/09/2004	11:25	-33.371	-70.179	8.6	4.6	Cortical
8	08/09/2004	08:16	-33.988	-72.318	31.9	5.1	Interplate
9	08/09/2004	08:06	-33.999	-72.399	33.5	4.7	Interplate
10	07/09/2004	12:33	-33.995	-72.352	17.9	5.3	Interplate
11	07/09/2004	10:57	-33.969	-72.418	36.3	5.3	Interplate
12	28/06/2004	18:08	-33.996	-72.289	28.3	4.3	Interplate
13	30/04/2004	10:03	-33.516	-70.566	95.8	5.4	Intraplate
14	20/09/2003	13:06	-33.235	-72.299	35.7	4.9	Interplate
15	18/07/2003	10:17	-33.826	-71.015	77.1	5.0	Intraplate
16	16/06/2003	15:10	-33.936	-71.111	71.6	5.2	Intraplate
17	30/05/2003	23:15	-33.822	-70.603	98.4	4.7	Intraplate
18	22/02/2003	18:04	-33.071	-71.278	56.7	4.8	Intraplate
19	07/01/2003	00:54	-33.778	-70.369	112.4	6.0	Intraplate
20	02/10/2002	21:40	-33.266	-69.828	5.6	4.0	Cortical
21	11/09/2002	13:34	-33.642	-72.064	28.6	4.6	Interplate
22	19/07/2002	06:55	-33.313	-70.752	81.0	5.2	Intraplate
23	10/05/2002	09:21	-33.361	-70.409	100.8	4.9	Intraplate

Table 3. Earthquakes recorded by CU stations since 1994 to 2000

Event	Date	Local time	Latitude (º)	Longitude (º)	Depth (km)	Magnitude	Type of earthquake
1	12/09/1994	23:07:1	-32.770	-71.638	33.3	4.8	Interplate
2	11/10/1994	01:37:2	-32.263	-71.532	45.8	5.4	Interplate
3	28/10/1994	20:59:2	-33.241	-70.477	76.5	4.9	Intraplate
4	22/02/1996	10:40:5	-33.634	-71.633	46.1	5.7	Interplate
5	02/03/1996	14:26:5	-33.296	-70.992	61.1	4.5	Intraplate
6	10/05/1996	14:22:5	-33.377	-70.356	104.1	4.6	Intraplate
7	24/07/1996	00:21:1	-33.027	-71.061	78.1	4.7	Intraplate
8	24/03/1997	21:14:4	-33.462	-70.784	82.7	5.4	Intraplate
9	20/04/1997	16:53:1	-34.001	-70.452	106.7	5.5	Intraplate
10	14/10/1997	22:03:3	-30.773	-71.315	58.0	6.8	Interplate
11	03/05/1998	19:42:3	-33.276	-71.473	44.9	5.0	Interplate
12	29/10/1998	16:55:5	-32.868	-70.662	85.8	5.0	Intraplate
13	12/01/1998	07:14:1	-31.101	-71.947	43.2	6.0	Interplate
14	17/04/1998	16:48:5	-32.787	-71.525	36.0	5.0	Interplate
15	10/10/1998	01:12:0	-33.543	-72.221	11.2	5.2	Interplate
16	04/04/1999	18:04:4	-33.625	-71.002	65.5	4.5	Intraplate
17	06/04/1999	04:45:3	-34.254	-72.037	40.0	4.9	Interplate
18	01/08/1999	22:06:4	-33.127	-70.339	98.8	5.1	Intraplate
19	03/08/1999	13:24:4	-32.817	-70.822	79.5	4.8	Intraplate
20	16/06/2000	04:55:3	-33.918	-70.391	115.2	6.0	Intraplate

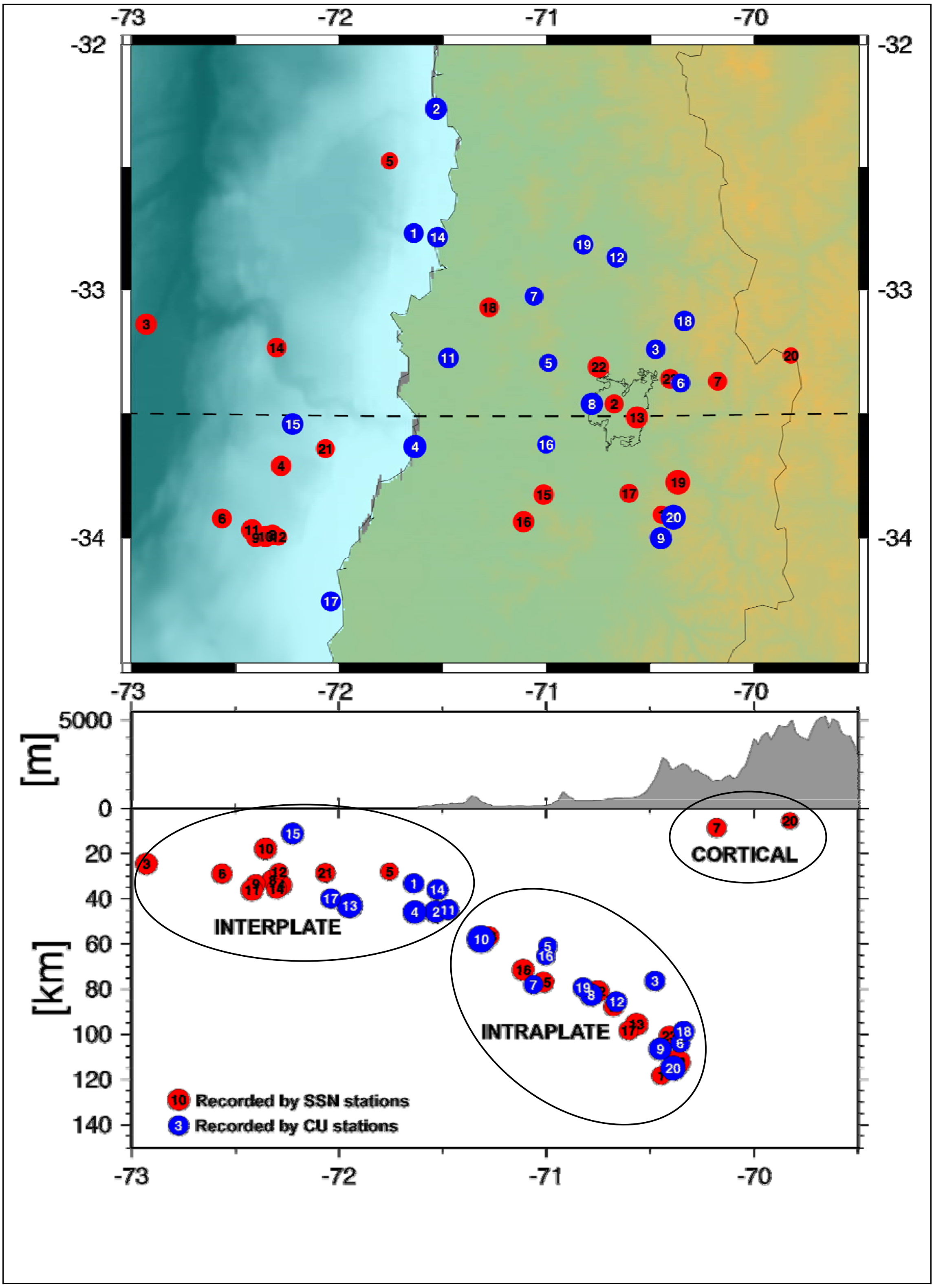
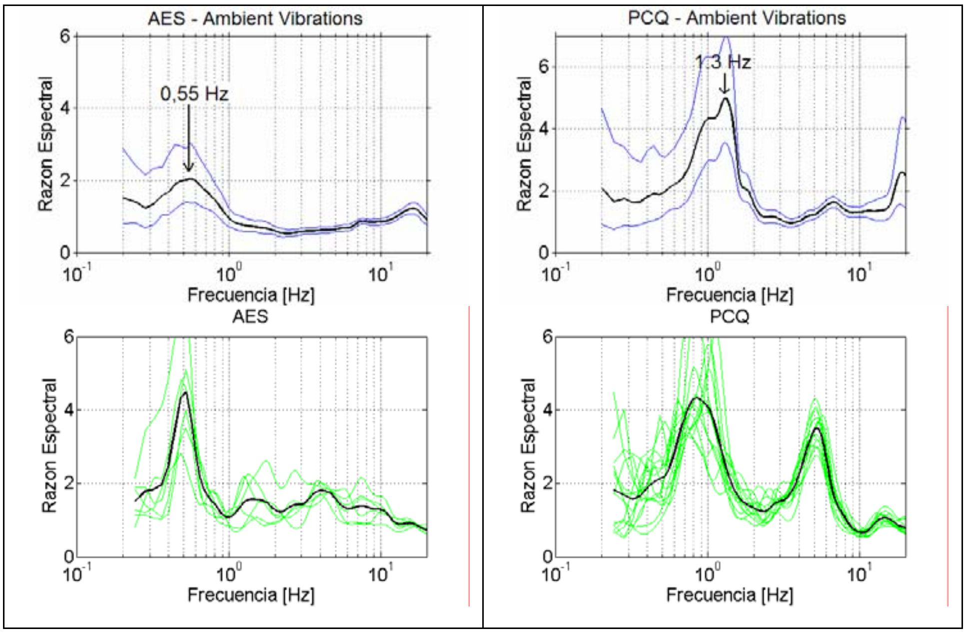


Fig. 2. Earthquakes recorded by SSN stations and CU stations

H/V SPECTRAL RATIOS

At the site where the seismic stations are located, using ambient vibrations, the H/V spectral ratios were computed (Nakamura, 1989). The noise records were carried out with a Lennartz seismometer, LE-3D/5s, and a Cityshark station continuously during 15 min at a sampling frequency of 125Hz. The recorded data were processed according to the following methodology: the stationary noise vibrations were selected from the recorded signal using a criterion of signal amplitude; where a short term window of 1 second and a long term window of 25 seconds were defined. The average amplitude of each window was identified as STA (short term average) and LTA (long term average). A stationary noise vibration was accepted when the ratio STA/LTA reached values between 0.25 and 1.75. Therefore, the selected parts of the signal or windows had a length of 25 sec, following the recommendations given by SESAME project that is likely one of the most important reference in the methodology of the H/V spectral ratio (Koller et al. 2004). Also, it was considered an overlap percentage of 50% between windows. The record was considered acceptable when it had at least 25 windows that satisfied the previous criterion. Then, the processing of individual windows for computing the H/V ratio was applied. A cosine taper with a length of 5% of the total window length was used on each component of the window, Vertical (V), Horizontal 1 (H1) and Horizontal 2 (H2). The FFT was applied to each component, so the three spectral amplitudes were obtained, which were smoothed using a function defined by Konno and Ohmachi (1998), with a bandwidth coefficient, b = 30. Thereafter, H/V ratios were computed, combining the horizontal components by a quadratic mean. Finally, the results of the different windows were averaged.

For each seismic station the H/V spectral ratios are presented in Fig. 3, including the mean value plus and minus one standard deviation. Additionally, the H/V spectral ratios computed from the recorded earthquakes are also presented. It can be seen that both ambient vibrations and earthquakes give similar results in terms of H/V spectral ratios at low frequencies, which can be considered as a good estimation of the predominant frequency. However, the ANTU station presents an H/V spectral ratio for ambient vibrations that is rather flat and it does not show a clear predominant frequency. However, a value around 1.0 Hz could be selected as natural frequency. One explanation of this behavior is associated with the high stiffness of the gravelly soil existing in this place, or the low impedance between soil and bedrock.



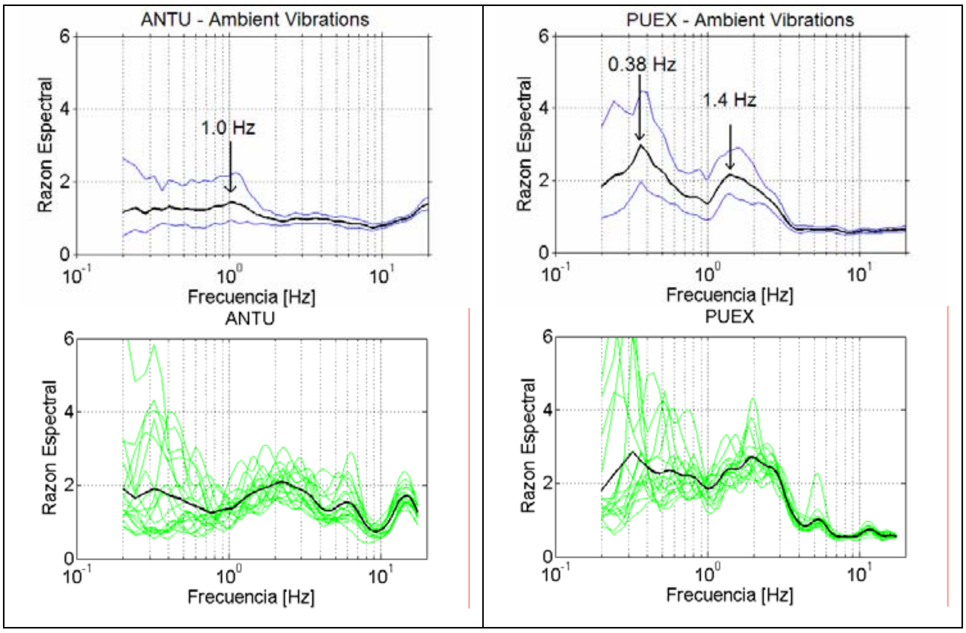


Fig. 3. H/V spectral ratios measured in different stations using ambient vibrations (top) and strong part of the recorded earthquakes (bottom).

PREDOMINANT FREQUENCIES OBSERVED IN THE RECORDED ACCELERATIONS

In order to investigate the predominant frequencies developed throughout the time history, the recorded accelerations of earthquakes in Table 2 and Table 3 were analyzed in detail via spectrograms. The adopted procedure to generate the spectrograms consisted in passing a window time where the Fourier transform was applied. The steps involved in this technique are briefly described: the signal was analyzed throughout temporal windows of five seconds, which were overlapped 50% (2.5 seconds). In each window the following steps were applied: base line correction, windowing with a cosine taper of 5% window length, FFT application, smoothing by moving averaging of 5 points and normalization of the spectrum by its maximum value. After this procedure was finished a characteristic time was associated with each window that corresponded to the mean time of each window. Therefore, the resulting normalized spectrum at any characteristic time has maximum amplitude of one.

Typical spectrograms obtained in seismic stations ANTU and PUEX for interplate earthquakes are presented in Figs. 4 and 5. While typical spectrograms obtained for intraplate earthquakes are presented in Fig. 6 and 7. It is interesting to observe that in the case of PUEX station, the H/V spectral ratio obtained from ambient vibrations present two peaks; one at 0.38 Hz and the second at 1.4 Hz.

On the other hand, it is observed that interplate earthquakes develop a predominant frequency along the acceleration time history that is quite similar to the fundamental frequency obtained from the H/V spectral ratio. Nevertheless, a predominant frequency in the acceleration time history of intraplate earthquakes is not observed. Similar results are also seen in the case of cortical earthquakes.

Due to the location of the interplate earthquake hypocenters, the generation of surface waves along the Santiago basin is fairly possible. On the contrary, both the intraplate and cortical earthquakes have less possibility of generating surface waves. Therefore, interplate earthquakes are expected to excite the modes associated with shear wave propagation, which is the theoretical background of the H/V spectral ratio.

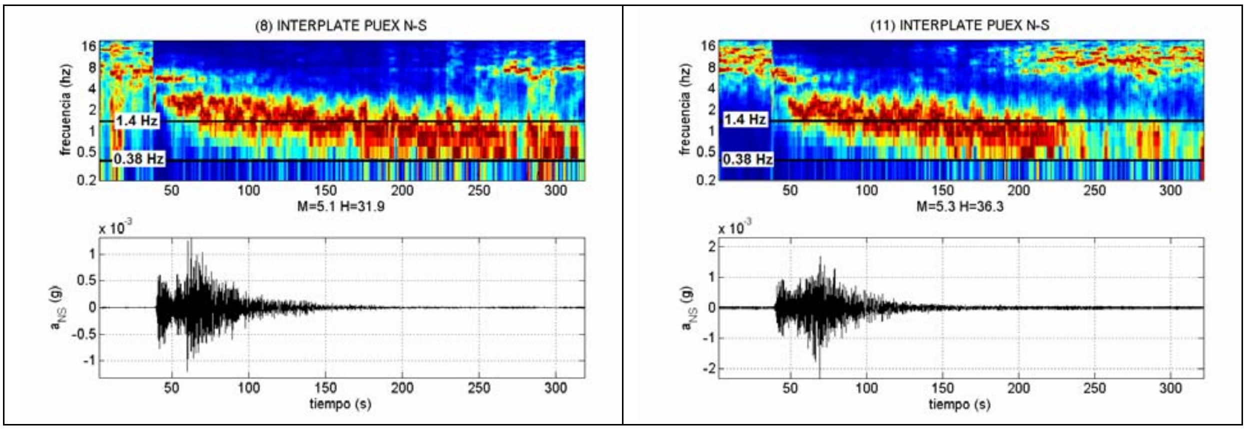


Fig. 4. Spectrograms of interplate earthquakes (8 and 11 in Fig. 2) recorded by PUEX station

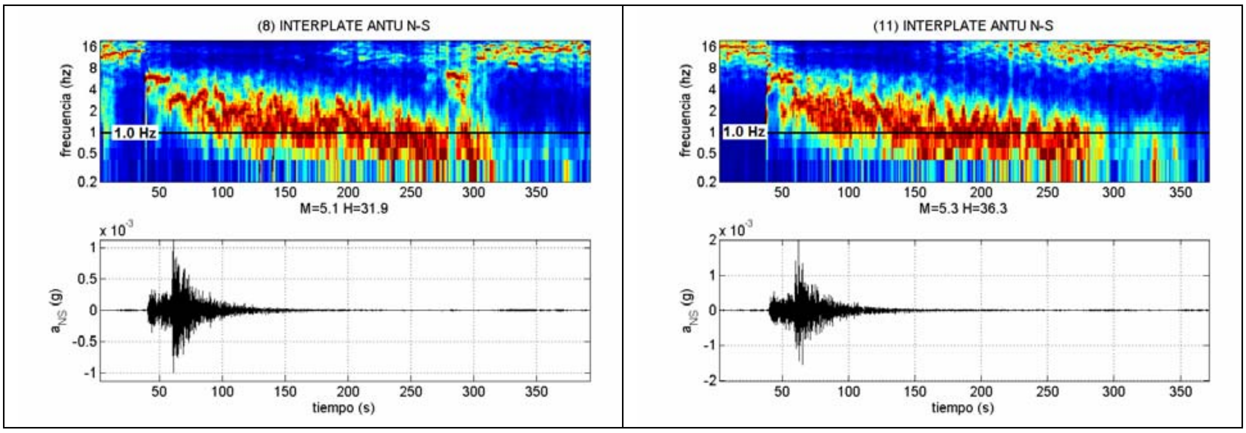


Fig. 5. Spectrograms of interplate earthquakes (8 and 11 in Fig. 2) recorded by ANTU station

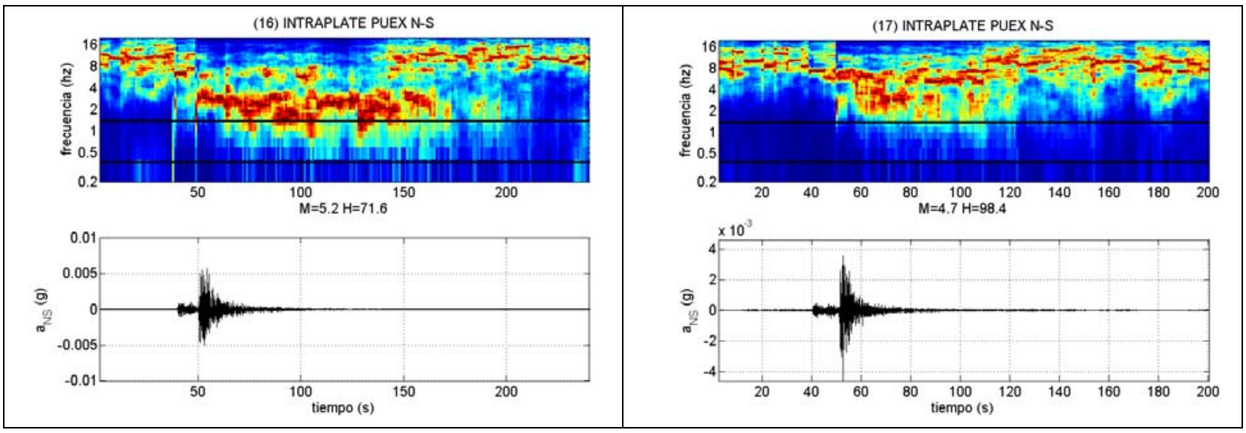


Fig. 6. Spectrograms of intraplate earthquakes (16 and 17 in Fig. 2) recorded by PUEX station

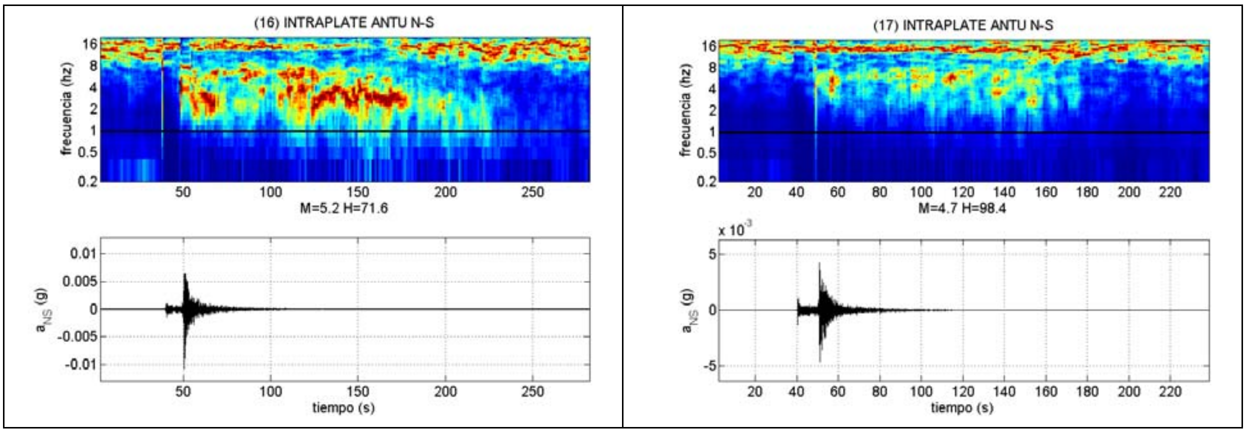


Fig. 7. Spectrograms of intraplate earthquakes (16 and 17 in Fig. 2) recorded by ANTU station

CONCLUSIONS

Santiago basin is located in a subduction zone environment with a high seismic activity, where at least three different seismic sources take place: interplate, intraplate and cortical earthquakes.

Ambient vibration measurements and recorded earthquakes at the ground surface have been used to compute the H/V spectral ratios. The results present similarities between both types of measurements in the low frequency range.

By means of spectrograms, the predominant frequencies along the accelerations records have been investigated. The results indicate that interplate earthquakes develop at the ground surface a predominant frequency that is quite similar to the fundamental frequency obtained by the H/V spectral ratios using ambient vibrations.

On the other hand, the motion observed at the ground surface, associated with intraplate and cortical earthquakes, do not present a predominant frequency, indicating that the main frequency of the horizontal accelerations depend on the type of earthquake.

The site amplification is controlled by both type of earthquake (interplate, intraplate and cortical) and the site characteristic (geotechnical properties of the ground and depth of the bedrock)

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