Earthquake Source Process and Site effects of Strong Motion stations of the 2010 Chile Mega-Earthquake

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We report on a reconnaissance survey on the seismological and geotechnical aspects of the 27 February, 2010 Maule mega-earthquake, Chile, carried out between April 27 and May 1, 2010. The survey was sponsored by the Japan Science and Technology Agency and JICA (SATREPS). In this study we surveyed the cities of Concepción Viña del Mar and Santiago. We also performed microtremors measurements at strong motion stations that recorded the earthquake. We will give an outline of the fault rupture process and strong motion characteristics of the earthquake and the site effects estimated from microtremor measurement.

Key Words : *2010 Chile earthquake, strong motion, source process, permanent displacement, site effects, microtremors H/V*

1. INTRODUCTION

The 2010/2/27 Maule (Chile) mega-earthquake, the fifth largest earthquake in instrumental history, was located in the subduction of the Nazca plate in Meridional Andes beneath the South American plate. This earthquake fills a well studied seismic gap between the source areas of the largest ever recorded 1960 Great Valdivia earthquake (M 9.5), and the 1985 Valparaiso earthquake (M7.8) [1)]. In this study we report on a reconnaissance survey on the seismological and geotechnical aspects of the 27 February, 2010 Maule mega-earthquake, Chile, carried out between April 27 and May 1, 2010. The survey was sponsored by the Japan Science and Technology Agency and JICA (SATREPS), under the framework of a newly launched 5 years SATREPS project entitled “Enhancement of Earthquake and Tsunami Disaster Mitigation Technology in Peru” [2)]. In this study we surveyed the heavily damaged city of Concepción, as well as moderately damaged cities of Viña del Mar and Santiago (Figure1). We performed microtremor measurements at strong motion stations that recorded the earthquake in order to evaluate their site characteristics. We also surveyed the damage to buildings due to tsunami effects in Dichato and Talcahuano among other areas but these results are reported elsewhere[3)].

Figure 1. Location of sites for field survey

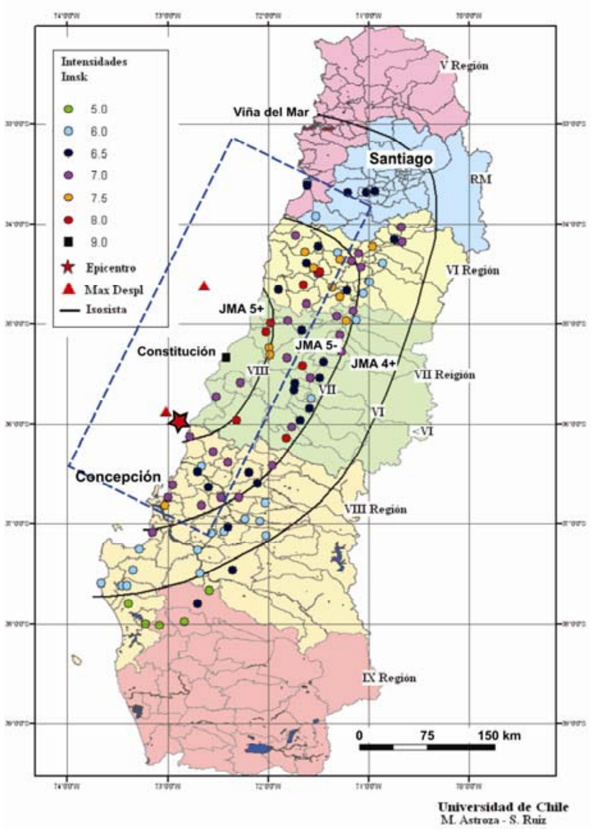

Figure 2. Intensity distribution of the Maule earthquake based on questionnaire survey[4].

2. SOURCE PROCESS OF THE MAULE EARTHQUAKE

The Maule earthquake ruptured a source area of nearly 450 km extending from southern Santiago in the North, down to the Arauco Peninsula south of Concepción city. The intensity distribution obtained from a questionnaire survey soon after the earthquake[4], indicates that a region of nearly 350 km above the fault plane experienced an intensity larger than 5 upper in the JMA intensity scale (Figure 2). This earthquake was an inter-plate mega-subduction event with a pure reverse mechanism, and had a seismic moment magnitude of 8.8 (Figure 3). The source rupture model of this earthquake was obtained by inversion of 38 P-wave teleseismic waveforms of the FDSN and GSN global seismic networks and using an inversion technique that incorporates an error component in Green's function calculation and the Akaike's Bayesian Information Criteria (ABIC) [5]. The source process is characterized by two asperities with a peak slip of more than 10 m and a rupture area of approximately 450 by 200 km^2 [6]. The first asperity is located at the hypocenter and the second is located approximately 150 km north-east of the hypocenter. The rupture propagated bilaterally starting slightly south of Constitución and with an average rupture velocity of 2.8 km/s, however the main moment release was located towards the North in the Pichilemu region. The source moment function has a total source duration of 150 s and display two sub-events separated by 30s (Figure 3). The average rake angle of this earthquake is 93 degrees which approximately corresponds to the oblique convergence of the Nazca plate beneath the South American plate.

3. STRONG MOTION CHARACTERISTICS

The Maule earthquake was recorded by 30 strong motion stations belonging to Universidad de Chile (Servicio Sismológico Nacional SSN, Geophysics department, 10 stations, and Red Nacional de acelerógrafos, RENADIC, Civil Engineering department, 20 stations). Instruments are mostly digital (21), and a large number of them is localized in Santiago (10) (Table 1). Published maximum PGA and PGV values reached

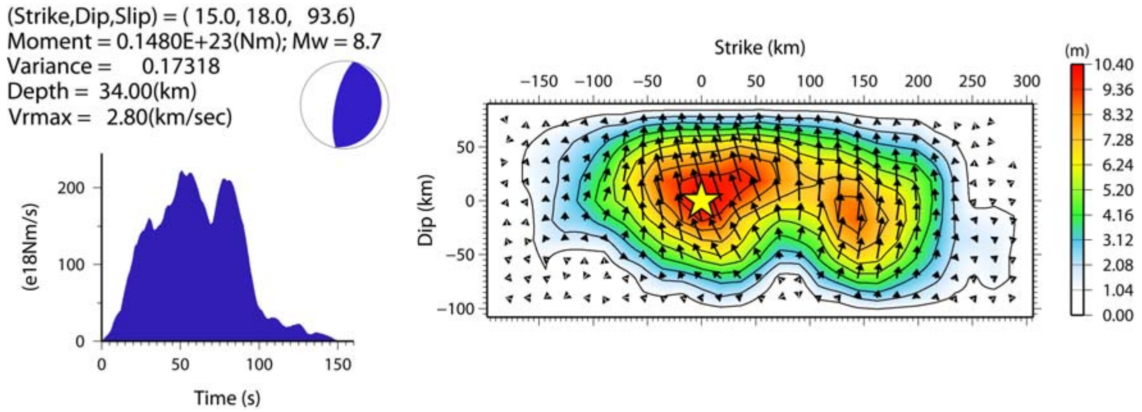

Figure 3. Source model of the 2010/02/27 Maule mega-earthquake (Chile)[6].

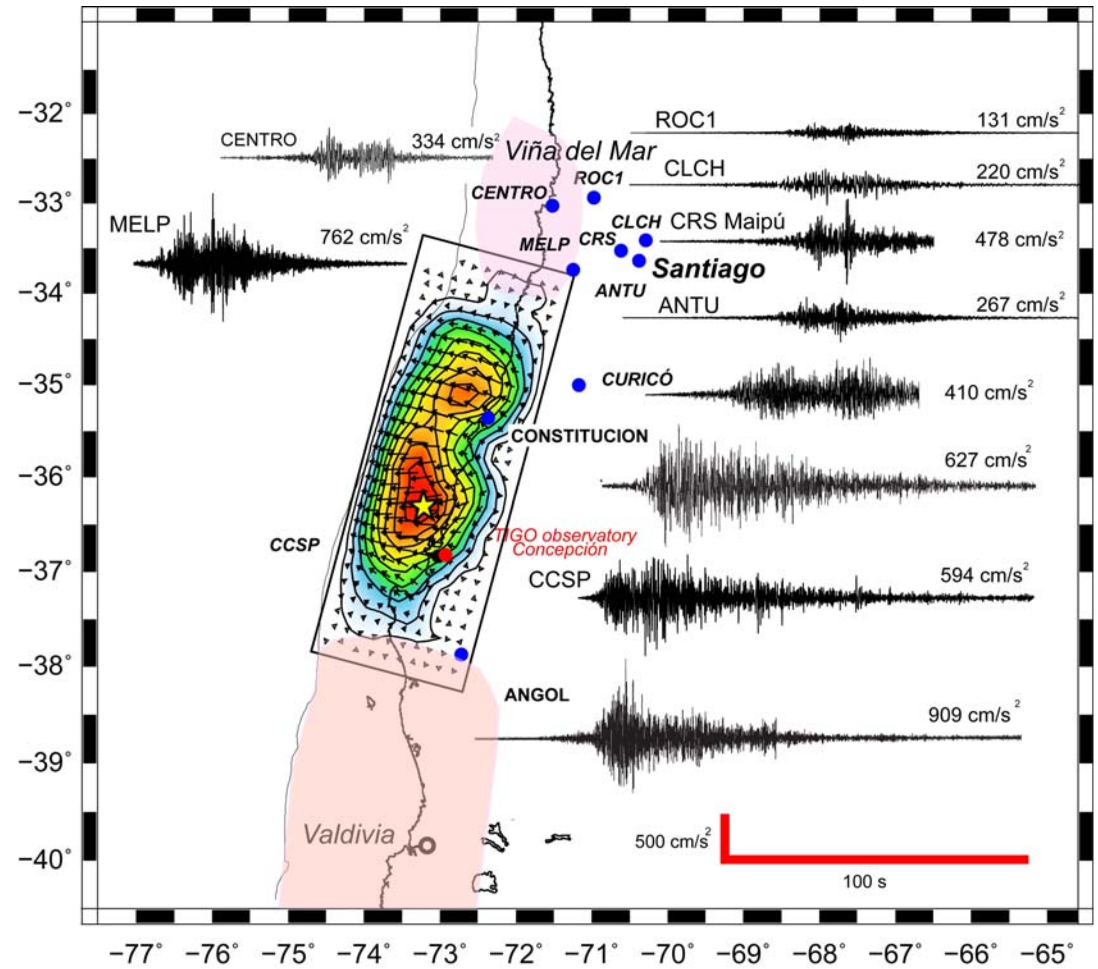

Figure 4. Source model and strong ground motion recordings of the 2010/02/27 Maule mega-earthquake (Chile)[6].

909 cm/s^2 at the Angol station south of Concepción, and 69 cm/s at Constitución (Table 1, Figure 4). Strong ground motions recorded in the northern region of the source area such as Curicó, Santiago and Viña del Mar display two clear sub-events separated by 15s to 30s, which is consistent with a rupture propagation velocity value of 2.8 km/s (Figure 4). Stations towards the central and southern regions of the source area such as Constitución, Concepción and Angol do not diplay distinct sub-events, as the rupture propagation of the northern asperity gradually runs away from southern stations. Angol station displays the largest PGA which

Table 1. Strong ground motion stations that recorded the 2010/02/27 Maule mega-earthquake

Station Location	**Station Code**	**Organization**	**Instrument Type**	**Longitude**	**Latitude**	**PGA (cm/s^2)**	**PGV (cm/s)**
Concepción	CCSP	SSN[2]	ETNA	-73.1087	-36.8443	637	44
Santiago (Campus Antumapu)	ANTU	SSN[2]	Episensor, Earth data	-70.6335	-33.5691	267	25
Cerro El Roble	ROC1	SSN[2]	Episensor, Q330 digitizer	-71.0156	-32.9759	184	21
Santiago (Cerro Galán)	CLCH	SSN[2]	SSA-120SLN, Terra Techn.	-70.5369	-33.3961	220	29
Melipilla	MELP	SSN[2]	QDR	-71.2138	-33.6874	762	46
Olmué (10 km West of El Roble)	OLMU	SSN[2]	QDR	-71.1730	-32.9940	347	28
Casablanca, Teatro municipal	CSCH	SSN[2]	QDR	-71.4108	-33.3208	322	44
San José de Maipó[1]	SJCH	SSN[2]	Makalu	-70.3510	-33.6440	471	63
Santiago (Colegio las Américas)	LACH	SSN[2]	Makalu	-70.5308	-33.4518	302	34
Santiago (Cerro Santa Lucía)	STL	SSN[2]	Makalu	-70.6428	-33.4405	332	46
Papudo (V Región)[1]	-	RENADIC[3]	SMA-1	-71.4440	-32.5090	413	25
Viña del Mar Marga-marga (V Región)	-	RENADIC[3]	ETNA	-71.5099	-33.0482	344	45
Viña del Mar Centro (V Región)	-	RENADIC[3]	QDR	-71.5508	-33.0253	327	33
Valparaíso UTFSM (V Región)	-	RENADIC[3]	SMA-1	-71.5956	-33.0346	261	16
Valparaíso Almendral (V Región)[1]	-	RENADIC[3]	SMA-1	-71.6130	-33.0560	298	29
Llolleo (V Región)[1]	-	RENADIC[3]	SMA-1	-71.6150	-33.6130	553	31
Santiago FCFM RM	-	RENADIC[3]	ETNA	-70.6617	-33.4572	162	22
Santiago centro RM (Based Isolated building Comunidad Andalucia)[1]	-	RENADIC[3]	SSA-2	-70.6520	-33.4670	303	26
Santiago Maipú RM (CRS Maipú)	-	RENADIC[3]	QDR	-70.7719	-33.5087	550	44
Santiago Peñalolen RM (Hospital Luis Tisne)	-	RENADIC[3]	QDR	-70.5792	-33.5006	289	29
Santiago Puente Alto RM (Hospital Sotero del Rio)	-	RENADIC[3]	QDR	-70.5811	-33.5769	260	31
Santiago La Florida RM (Linea 5, Mirador)	-	RENADIC[3]	K2	-70.6060	-33.5135	231	19
Matanzas (VI Región)	-	RENADIC[3]	SMA-1	-71.8734	-33.9604	335	43
Hualañe (VII Región)	-	RENADIC[3]	SMA-1	-71.8053	-34.9765	452	39
Curico (VII Región)	-	RENADIC[3]	QDR	-71.2364	-34.9808	461	33
Talca (VII Región)	-	RENADIC[3]	SMA-1	-71.6649	-35.4299	467	33
Constitución (VII Región)	-	RENADIC[3]	SMA-1	-72.4057	-35.3401	627	69
Concepción (VIII Región), Colegio Inmaculada Concepción	-	RENADIC[3]	SMA-1	-73.0483	-36.8281	394	68
Angol (IX Región)	-	RENADIC[3]	QDR	-72.7081	-37.7947	909	38
Valdivia (XV Región)	-	RENADIC[3]	QDR	-73.2133	-39.8244	135	18

Notes

[1] approximate station coordinates from Google Earth

[2] Servicio Sismológico Nacional, Universidad de Chile

[3] Red Nacional de Acelerógrafos, Universidad de Chile

[4] Most infomation for this table was compiled from [7,8,9,10)]

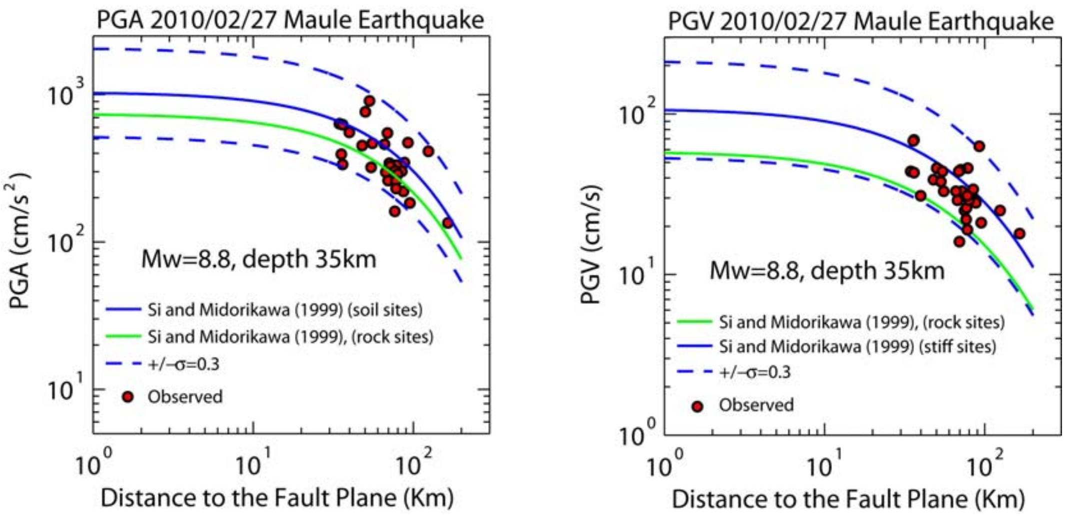

Figure 5. Attenuation of PGA and PGV for observed strong motions Maule mega-earthquake

indicates the possibility of large slip below the Arauco peninsula (around latitude -37.5 degrees), that is not sufficiently simulated in our current slip model. In fact a recent study indicates that the Arauco peninsula experienced a maximum coseismic uplift of 2.5m along the coast, suggesting that the source area could have reached a latitude as far as -38 degrees[11)], which approximately corresponds the northern end of the 1960 Valdivia earthquake.

In Figure 5 we plotted the PGA and PGV attenuation characteristics of observed strong ground motions of the Maule earthquake, for all the sites described in Table 1. We plot the data together with an empirical relationship of PGA and PGV for inter-plate subduction earthquakes (Mw=8.8, depth 35 km) for soil, stiff soil and rock site conditions[12)]. We may observe that all observed data falls within one sigma (+/-0.3) around the values for a stiff soil. This result implies that the observed peak ground motions characteristics from the Maule earthquake can be satisfactorily explained by a typical empirical attenuation relationship for inter-plate subduction earthquakes.

4. COSEISMIC PERMANENT DISPLACEMENTS

GPS measurements from the Maule earthquake in South America indicate a coseismic displacement to the West as large as 3m at the CONZ station in Concepción (Figure 6). CONZ is a high sampling GPS (cGPS) station located at the Transportable Integrated Geodetic Observatory (TIGO), which recorded in real time the Maule earthquake [13)]. We attempted to calculate the permanent displacement at Concepción by using a strong motion recording of the earthquake at the CCSP station, which is closely located to the TIGO observatory. For that purpose we double integrated and de-trended the unfiltered acceleration data. Our results show nearly 3m of permanent displacement to the West, which is in very good agreement with the results by the cGPS recording at TIGO (Figure 7). Displacement time series obtained from this strong ground motion recording are also in close agreement with the observed cGPS from the arrival of the rupture up the static displacement value.

We also calculated the coseismic vertical displacements along the coastline by using our source model of the Maule earthquake (Figure 3) and analytical expressions for strains and displacements in a half space due to shear dislocations[15)] (Figure 8). Our simulation results show in general a good aggreement with the observed uplift/subsidence values along the coast, estimated from changes in coral algae[11)] as well as high sampling GPS measurements at the TIGO geodetic observatory [CONZ] (Figure 8). However our simulated vertical displacements underestimate the observed values at the Arauco peninsula, suggestting larger values of coseismic fault slip beneath the Peninsula (Figure 8).

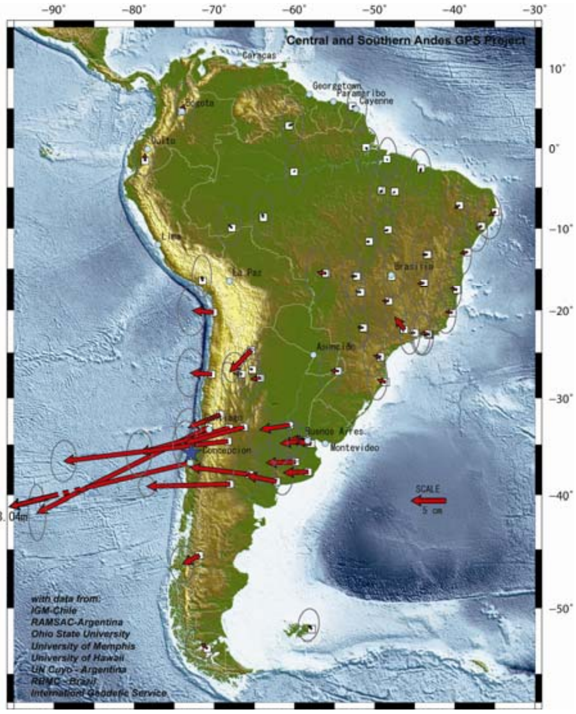

Figure 6. Coseismic displacements at South American GPS stations during the 2010/02/27 Maule mega-earthquake (Chile). Displacements at Concepción are as large as 3 m to the West[14].

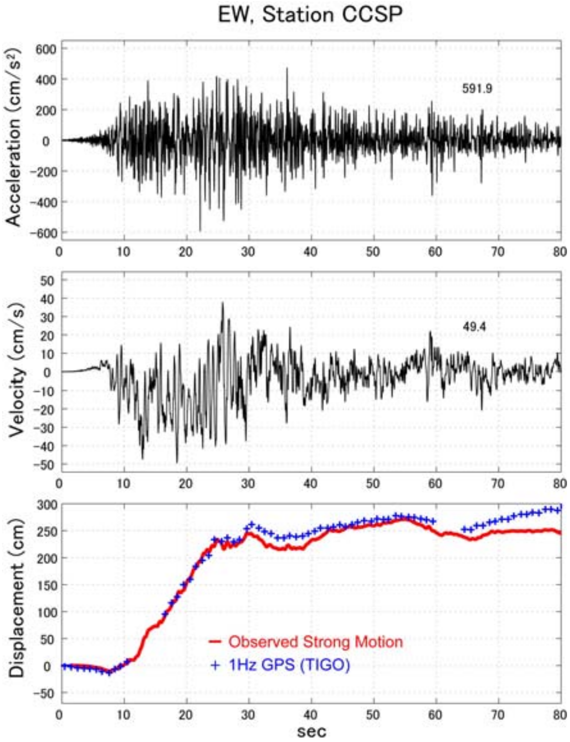

Figure 7. Strong ground motion recording of the 2010/02/27 Maule mega-earthquake (Chile) at the Colegio San Pedro (Concepción), strong motion site. Upper panel shows the unfiltered acceleration, middle panel the unfiltered and de-trended velocity, and the lower panel the calculation of the permanent displacement at this station [6].

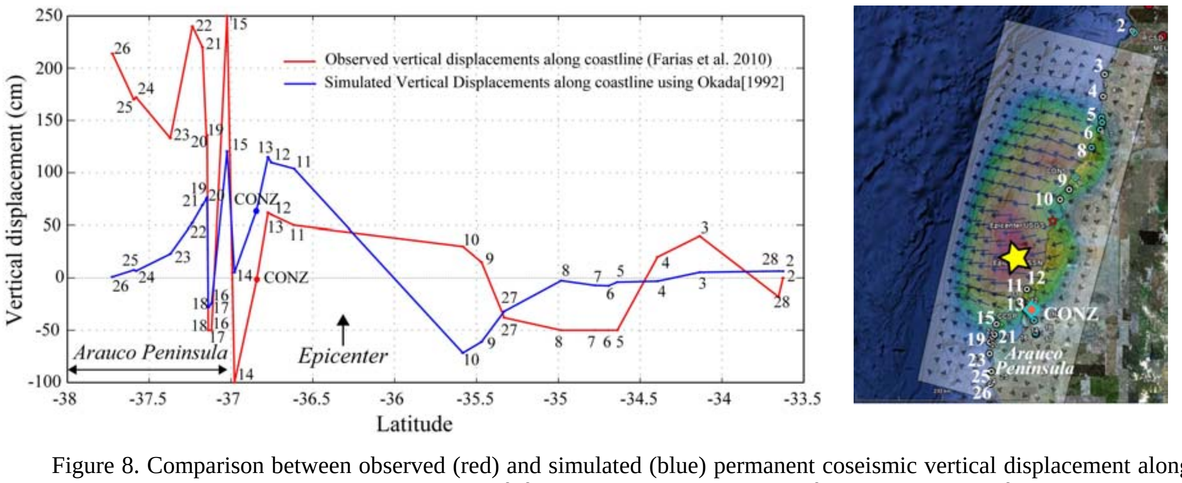

Figure 8. Comparison between observed (red) and simulated (blue) permanent coseismic vertical displacement along the coast during the 2010 Maule earthquake (left figure). Observed vertical uplifts where measured from observation of changes in coral algae along the coast [11]. Right figure shows the location of vertical displacement measurement points.

5. MICROTREMORS MEASUREMENS AT STRONG MOTION SITES

In order to estimate the site characteristics at strong motion sites that recorded the mainshock we performed microtremors measurements in Santiago, Concepción and Viña del Mar cities. The microtremors measurements where performed by using a velocity sensor with predominant period of 2s and a sampling frequency of 200 Hz. Measurement time at each site was set to 300s.

(1) Measurements at Santiago city

We surveyed two areas in Santiago city. The first area (MPS) is the RENADIC Santiago Maipú RM strong

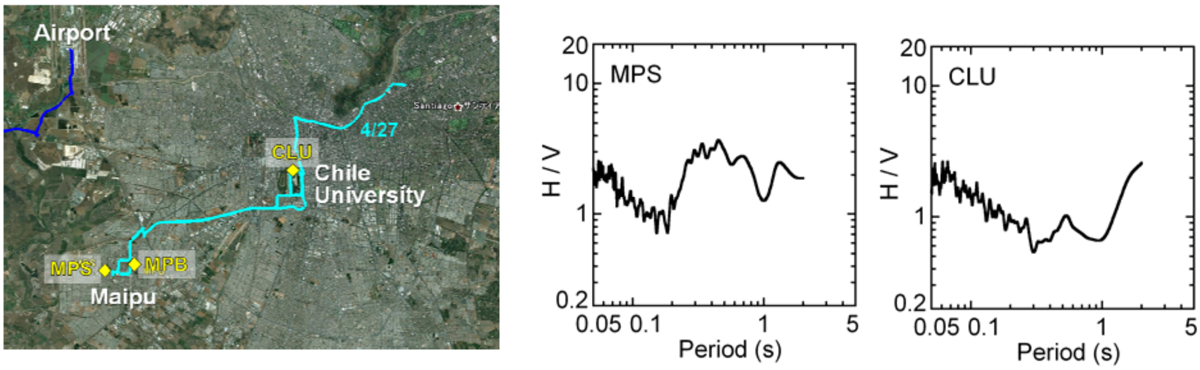

Figure9. H/V of microtremors measurements near strong motion station Maipu [MPS], and Chile university [CLU] in Santiago city

motion station located in the western region of the city (Figure 9). We found sevearl heavy damaged buildings around this area. We also surveyed the area near Chile university in the center of Santiago city (CLU). In this case our survey indicates no building damage around this area. Our H/V measurements at MPS indicate a clear peak around 0.4s. This site experienced a PGA value of 550 cm/s^2 and a PGV of 44 cm/s respectively. On the other hand H/V measurements at CLU don't show a clear peak. These measurements suggest that the site effects may have had a contribution to the building damage near MPS.

(2) Measurements at Concepción city

In Figure 10 we show the microtremors measurements sites as well as other survey sites on a microzonation map of Concepción city[17]. This microzozonation is based on H/V measurements as well as other geological and geotechnical information. A yellow region on the map (Z-I) corresponds to H/V peaks of 1.0-1.4s. We can observe that the dowtown area is largely characterized by a predominant peak around 1s. On the other hand in the South-West area of downtown runs the Bio-Bio river which suggest that the soil condition in this region

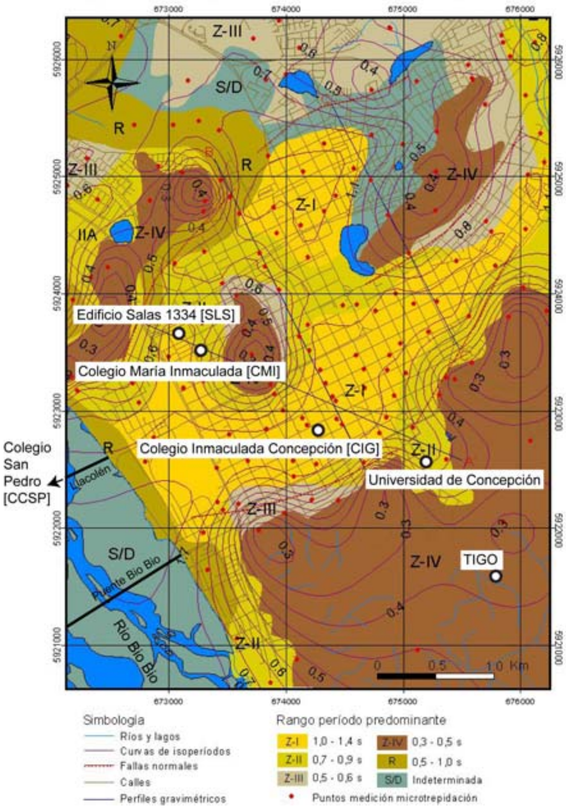

Figure 10. Microzonation map of Concepción city[16]. Survey sites are shown within the figure

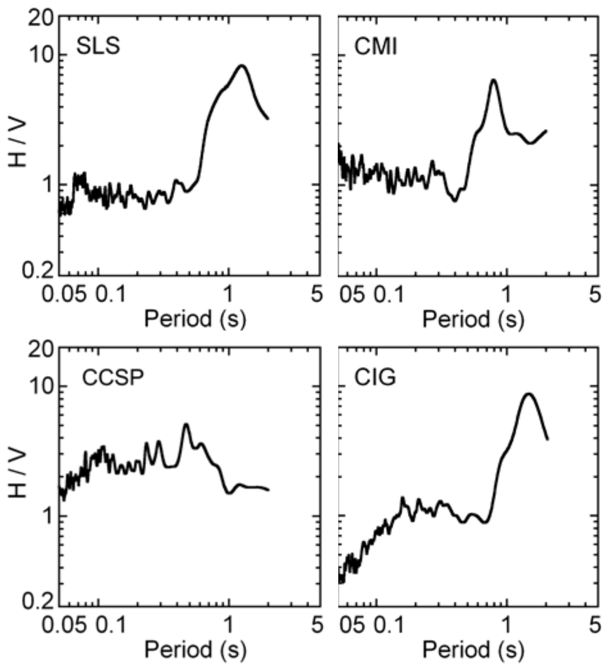

Figure 11. H/V ratios of microtremors in downtown Concepción city

might be characterized by thick alluvial deposits. We performed microtremors measurements at four sites including two schools in down-town; Colegio inmaculada Concepción (CIG), Colegio María Inmaculada (CMI), a heavily damaged (to be demolished) 12 stories reinforced concrete building (Edificio Salas 1334, SLS), and another school located in the opposite shore of the Bio-Bio river in a mountain footslope area (Colegio San Pedro) (Figure 10). Our H/V measurements at CIG and SLS show a predominant peak larger than 1s, and a peak of 0.7s at CMI (Figure 11). The heavy damage sustained at SLS might be related with the large H/V peak at this site. The underground floor of the CIG building accomodates a RENADIC analogue acelerograph that recorded a PGA value of 394 cm/s^2 and a PGV of 68 cm/s. This building sustained a moderate damage and according to the shool principal an older section of the school also experienced the 1960 Valdivia earthquake. Our H/V measurements at Colegio San Pedro where located near the CCSP strong motion station within the school premises. This site recorded a PGA value of 637 cm/s^2 and a PGV of 44 cm/s. The school is built on a sandy soil area within a small valley, and the CCSP is located at the egde of the valley near a slope. A 1 story classroom located close to the strong motion station sustained significant damage produced by subsidence of the ground. Although H/V measurements close to the CCSP station do not show significant peaks (Figure 10), another H/V measurement at the school ground in the middle of the valley show a clear peak around 0.3s. This indicates that the CCSP station is located at the edge of the valley sandy soil deposits[18)].

(3) Measurements at Viña del Mar city

We surveyed two areas in down town Viña del Mar. The first area (VMS) is located in the southern region of the Marga Marga river close to the RENADIC Viña del Mar Centro strong motion station (Figure 12). Our survey indicates no building damage around this area. We also surveyed the area to the north of Marga-Marga river (VMB). In this case we found a heavy concentration of damage to medium rise apartment buildings. Our H/V measurements at VMS indicate a clear peak around 0.4s. This site experienced a PGA value of 327 cm/s^2 and a PGV of 33 cm/s respectively. On the other hand H/V measurements at VMB show a clear peak at 1s. These measurements suggest that the site effects may have had a big contribution to the building damage at VMB, and indicate the ground motion might have been stronger at the Nothern part of Marga-Marga river compared to the Southern area.

6. CONCLUSIONS

We performed a field survey of the 2010 Chile earthquake which included visits to several universities in Santiago, Concepción and Viña del Mar, as well as microtremor measurements near strong motion stations at these cities. Near-source strong ground motions characteristics of the mainshock are largely influenced by complexity in source rupture process. On the other hand ground motion attenuation characteristics of this earthquake can be satisfactorily explained with a typical empirical law for inter-plate subduction earthquakes. Based on a strong motion recording of the mainshock we obtained a 3m permanent displacement to the west at Concepción city, which is in very good agreement with the results obtained by a 1Hz GPS recording of the earth-

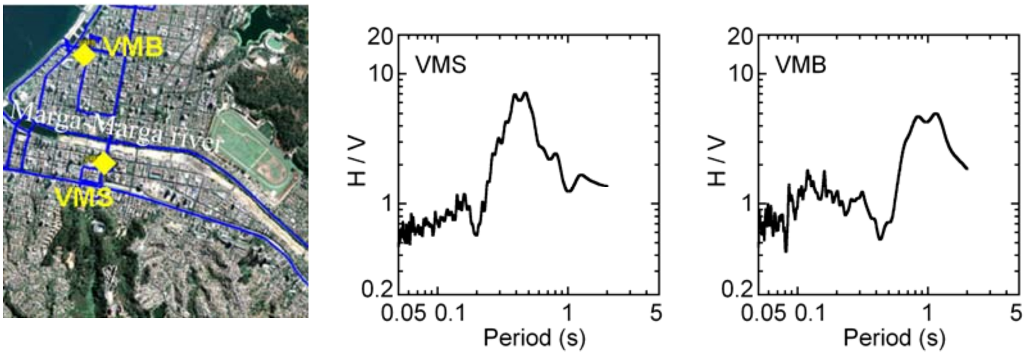

Figure12. H/V of microtremors measurements near strong motion station Viña del mar Centro [VMS], and within the building damage area [VMB] in Viña del mar

quake at the TIGO observatory in Concepción. Our theoretical calculations of coseismic displacements along the coast are also in good agreement with the observed data. Our microtremors measurements and field survey indicates a clear relationship between site effects and building damage. Future research work includes the improvement of our source model using constraints from near-source data as well as the strong motion simulation of this earthquake.

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