2010 CHILE EARTHQUAKE AND TSUNAMI TECHNICAL REPORT

By

JST-JICA SATREPS PERU PROJECT

CHILE EARTHQUAKE FIELD INVESTIGATION TEAM

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Forward

This technical report contains five individual papers written by the members of the 2010 Maule, Chile, earthquake/tsunami survey teams sponsored by Japan Science Technology Agency (JST). The 2010 Chile earthquake occurred off the coast of the Maule Region of Chile on February 27, 2010, at 03:34 local time (06:34 UTC) with moment magnitude of 8.8. As a part of an international research project “Enhancement of earthquake and tsunami disaster mitigation technology in Peru”, which is under the research program “Science and Technology Research Partnership for Sustainable Development (SATREPS)” supported by the Japan Science and Technology Agency (JST) and the Japan International Cooperation Agency (JICA), three survey teams consisting of Japanese and Peruvian researchers were dispatched to the affected areas from early April to early May, 2010. The reason why such an international group conducted field survey is that the lessons learned from the 2010 Chile earthquake are expected to apply to earthquake/tsunami disaster mitigation technologies in Peru also because the two countries have common regional tectonics and similar natural/social environments.

The first survey team performed quick damage data collection with the aid of GPS and high-resolution satellite images. Geo-referenced photos and videos were taken in the hard-hit areas. The results of the field survey and data analysis are presented in the paper by Yamazaki et al. (2010).

The second survey team, consisting of tsunami scientists, focused on the measurements of tsunami inundation/run-up height, flow depth, extent of inundation zone, structural damage inspection, and collecting eyewitness accounts. The paper by Koshimura et al. (2010) summarized the tsunami data collected in their survey.

The third survey team, consisting of structural engineers, geotechnical engineers, and seismologists, conducted the field investigation from the view points of strong motion, local site effects, and building damage. The paper by Pulido et al. (2010) provides the information on the source process and the results of microtremor measurement at seismic recording sites. The paper by Shoji et al. (2010) summarized the damage observation of houses and infrastructures, affected by both strong motion and tsunami. The paper by Saito et al. (2010) presents the detailed information of damaged buildings due the earthquake.

Although our investigation is still preliminary, we want to share the observations and lessons learned from the event internationally. During the field survey, the team members were assisted by many Chilean government officers, researchers and engineers. We express sincere appreciation to all these supports.

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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

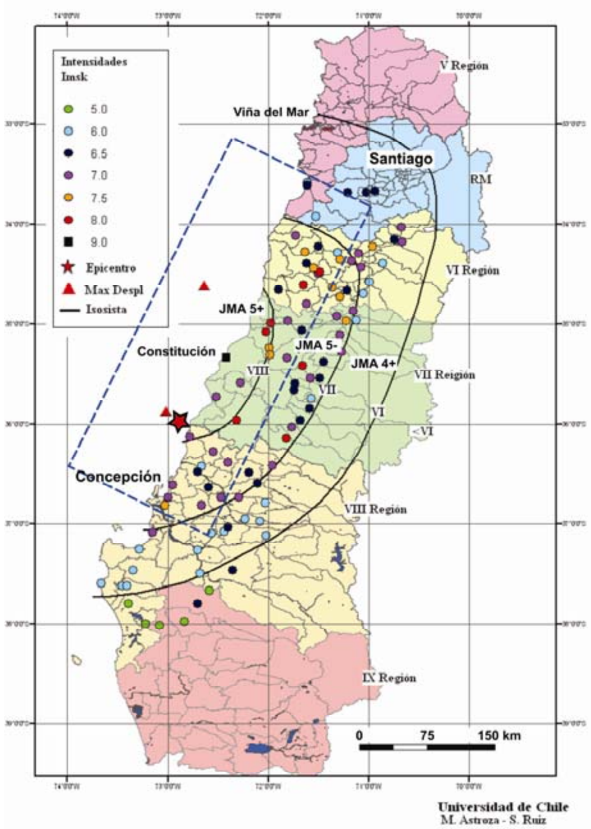

Figure 2. Intensity distribution of the Maule earthquake based on questionnaire survey[4].

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

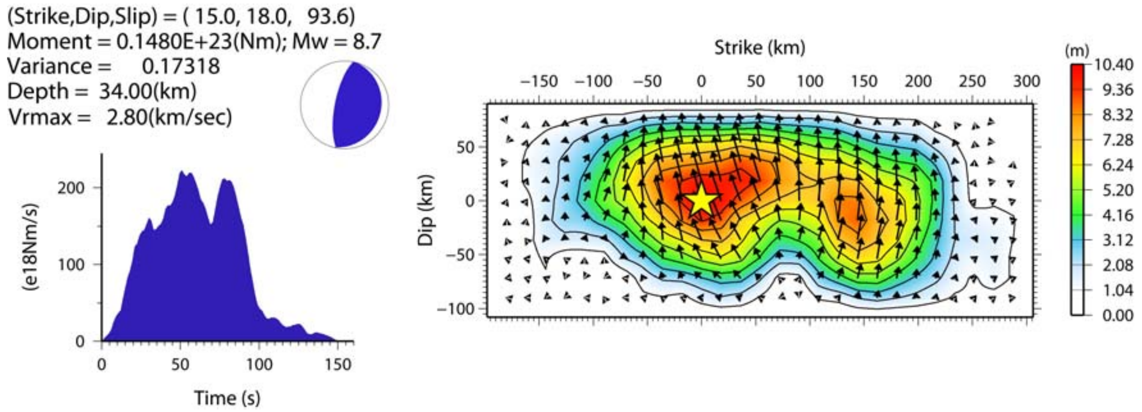

Figure 3. Source model of the 2010/02/27 Maule mega-earthquake (Chile)[6].

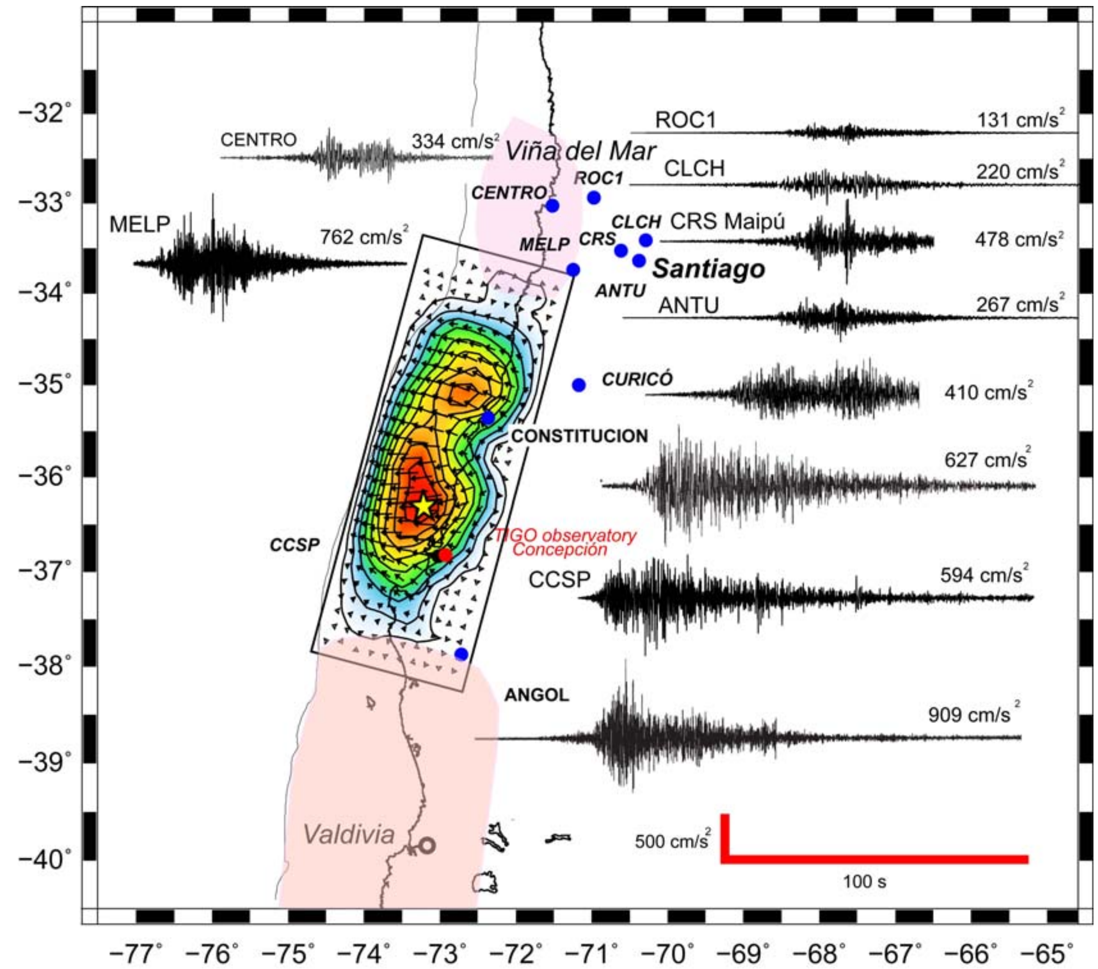

Figure 4. Source model and strong ground motion recordings of the 2010/02/27 Maule mega-earthquake (Chile)[6].

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)]

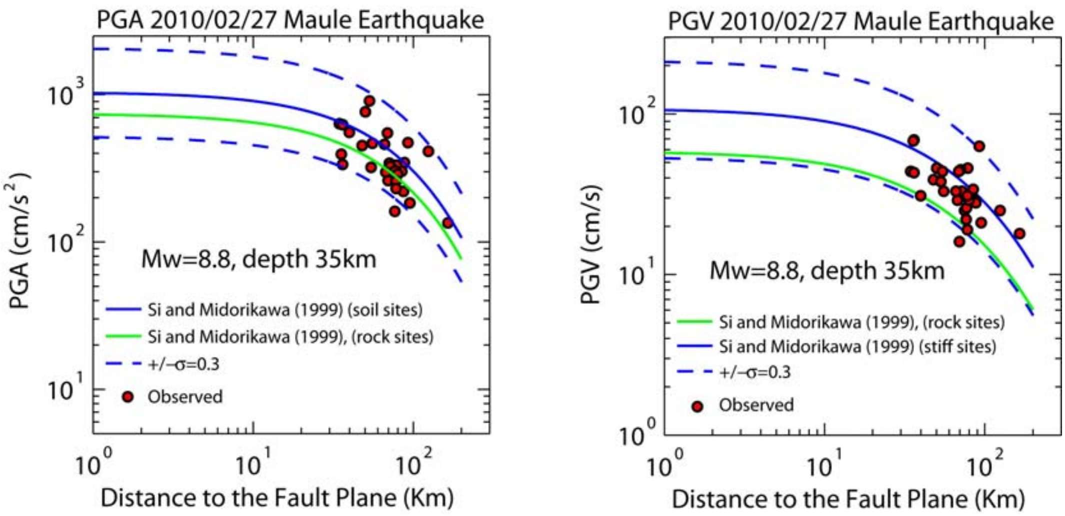

Figure 5. Attenuation of PGA and PGV for observed strong motions Maule mega-earthquake

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).

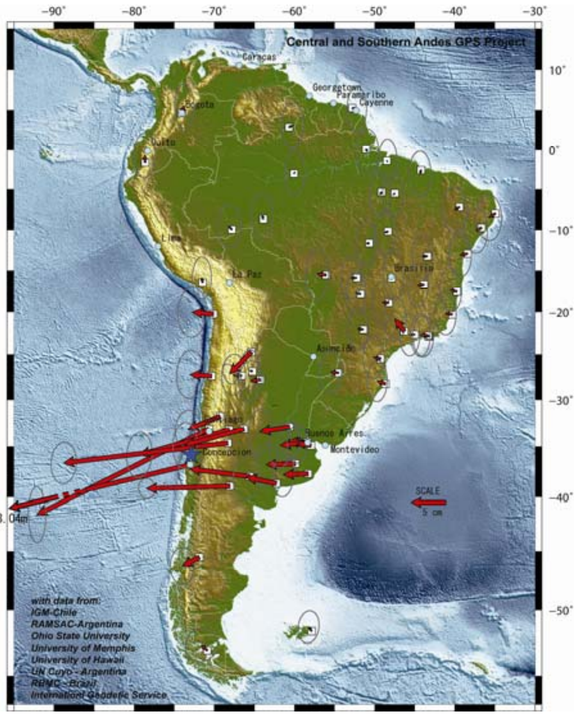

Figure 6. Coseismic displacements at South American GPS stations during the 2010/02/27 Maule mega-earthquake (Chile). Displacements at Concepción are as large as 3 m to the West[14].

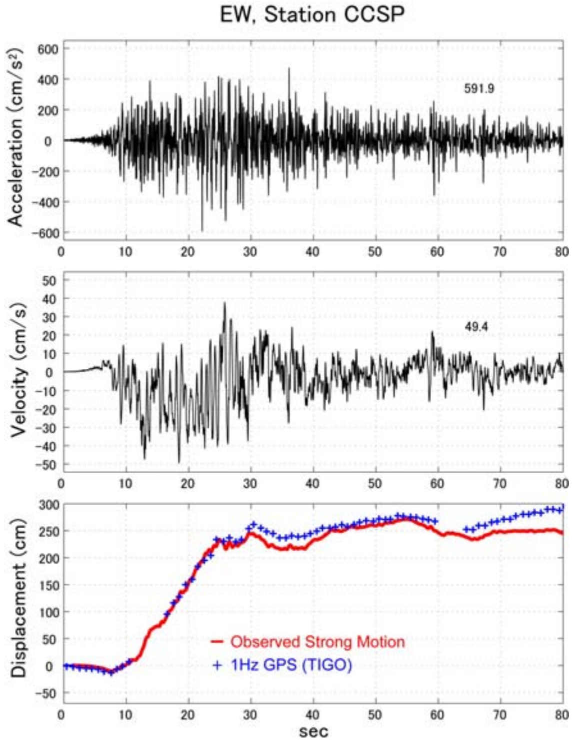

Figure 7. Strong ground motion recording of the 2010/02/27 Maule mega-earthquake (Chile) at the Colegio San Pedro (Concepción), strong motion site. Upper panel shows the unfiltered acceleration, middle panel the unfiltered and de-trended velocity, and the lower panel the calculation of the permanent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

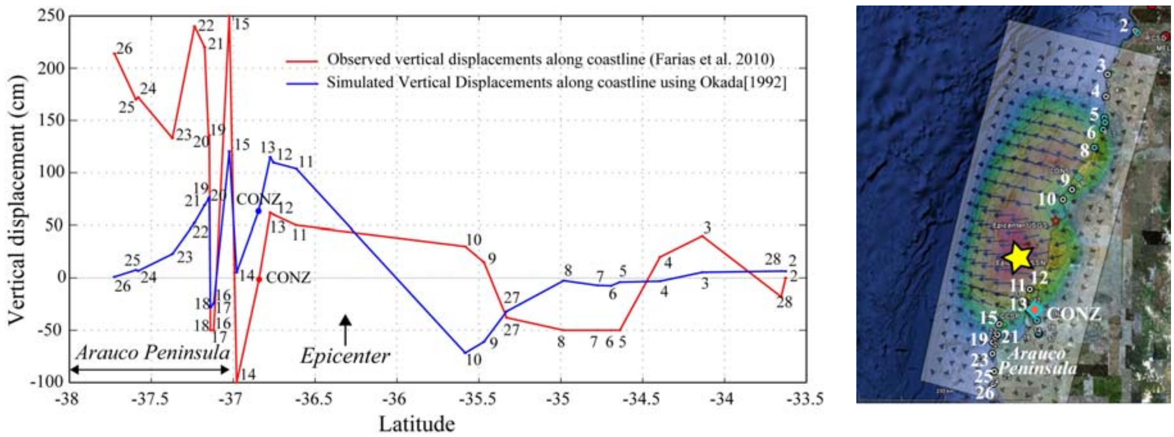

Figure 8. Comparison between observed (red) and simulated (blue) permanent coseismic vertical displacement along the coast during the 2010 Maule earthquake (left figure). Observed vertical uplifts where measured from observation of changes in coral algae along the coast [11]. Right figure shows the location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

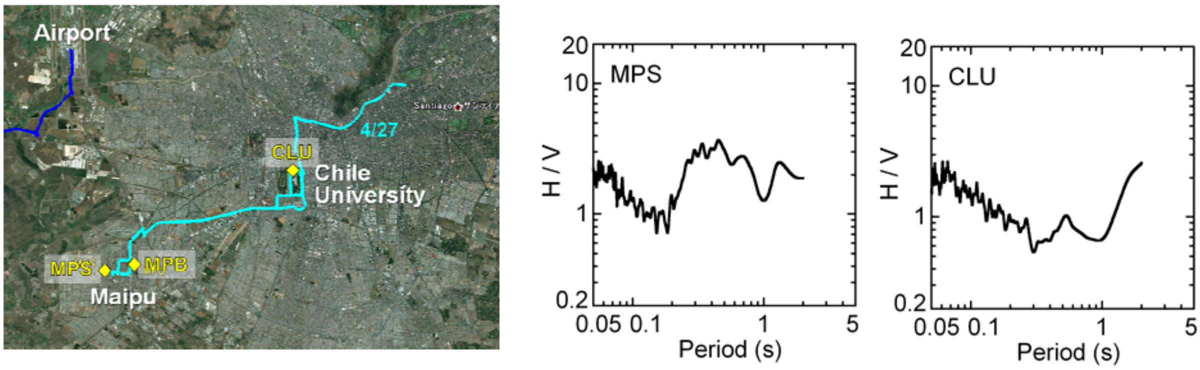

Figure9. H/V of microtremors measurements near strong motion station Maipu [MPS], and Chile university [CLU] in Santiago city

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

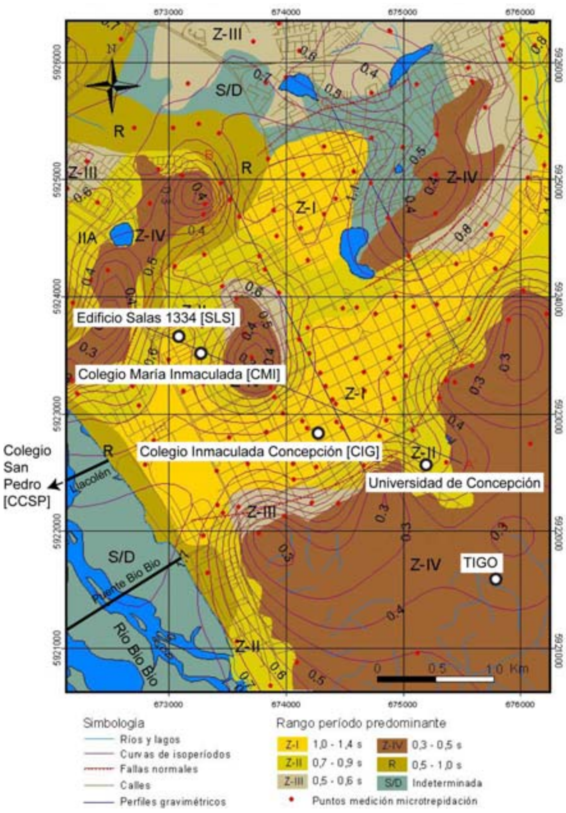

Figure 10. Microzonation map of Concepción city[16]. Survey sites are shown within the figure

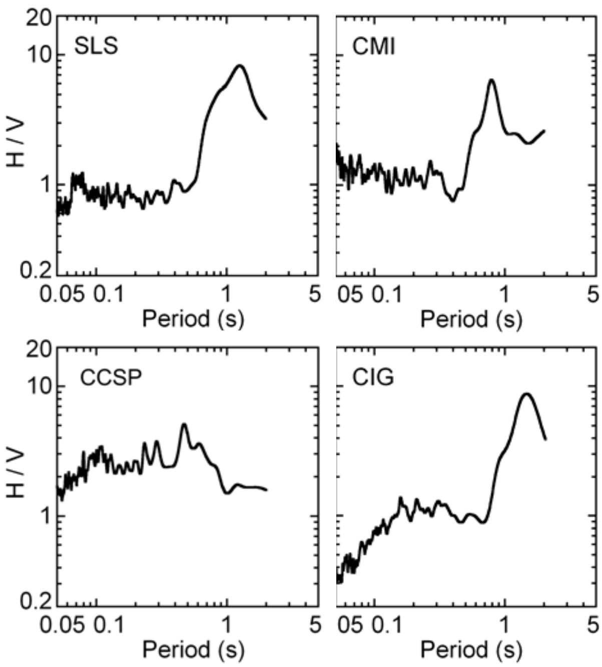

Figure 11. H/V ratios of microtremors in downtown Concepción city

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 accelerograph 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-

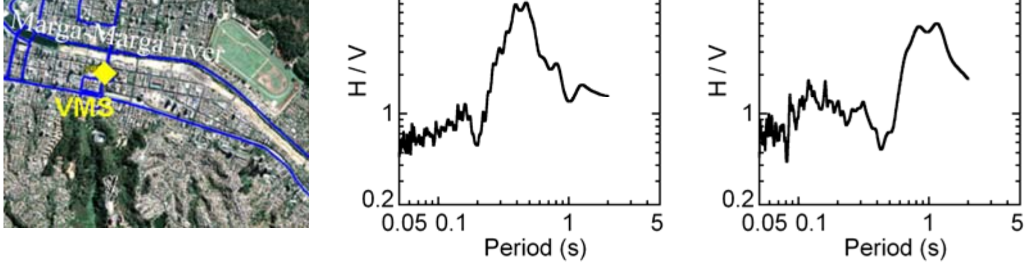

Figure12. H/V of microtremors measurements near strong motion station Viña del mar Centro [VMS], and within the building damage area [VMB] in Viña del mar

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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Field survey of the 2010 tsunami in Chile

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We conducted the field survey of the tsunami generated by the M8.8 great earthquake in Chile triggered on 27 February 2010 (UTC). The survey focused on the measurements of tsunami inundation/run-up height, flow depth, extent of inundation zone, structural damage inspection, and collecting eyewitness accounts. In total, tsunami heights and flow depths at approximately 155 points were measured along the coast of Biobio region, Chile, to understand the tsunami features during this event.

Key Words :*The 2010 Maule earthquake, tsunami, field survey*

1. INTRODUCTION

On 27 February 2010, a megathrust earthquake of M8.8 (**Fig.1**) generated a destructive tsunami. It struck not only Chilean coast but propagated all the way to Japan. After the event occurred, the post-tsunami survey team was assembled, funded by JST, to survey the area of severely affected by the tsunami. The main purpose of the survey was to examine the damage, measure the tsunami run-up and inundation height, flow depth and extent of inundation, and interview the eyewitnesses of the tsunami. A joint survey team was consisted of the members from SATREPS and the researchers from Central Research Institute of Electric Power Industry (5 researchers from Japan and two researchers from Peru).

The following report aims to describe the findings and knowledge from the survey.

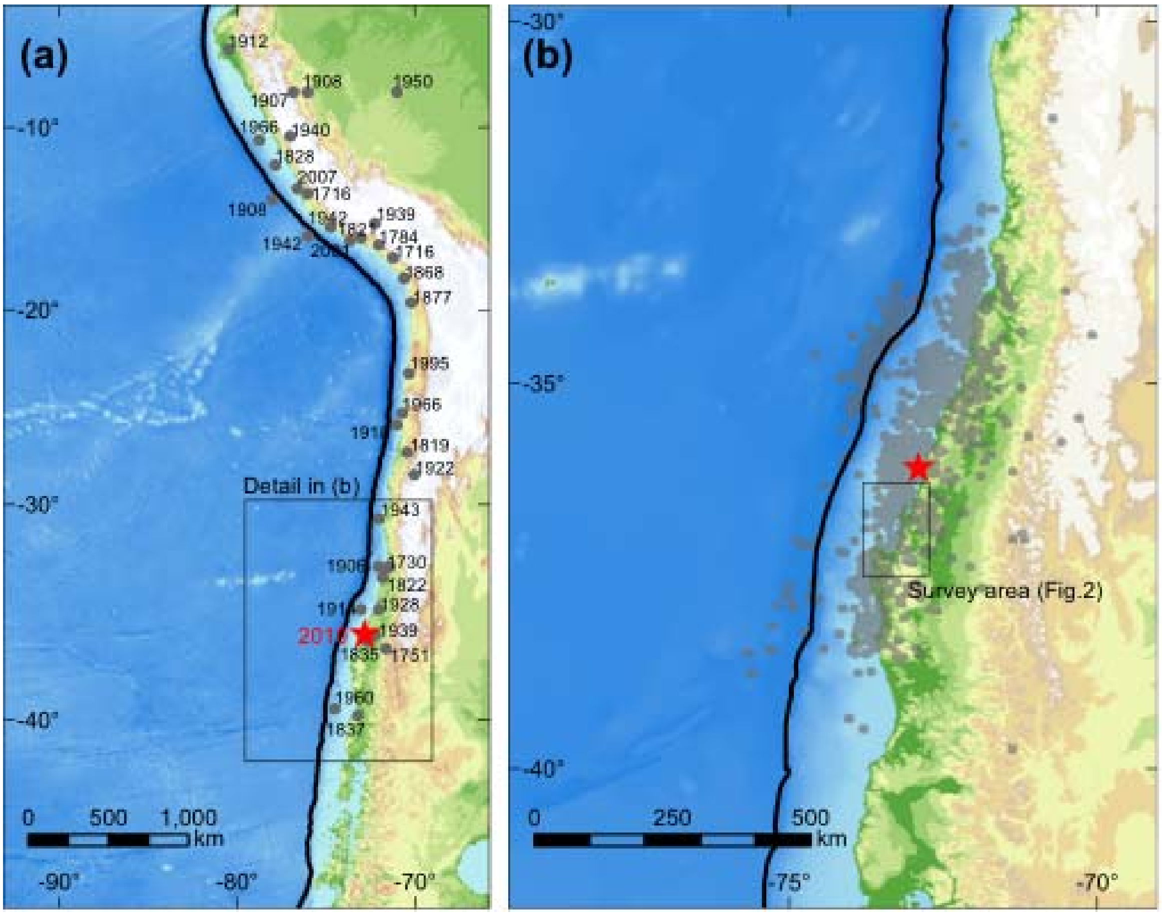

Fig.1 (a) Significant earthquakes of more than M8 since 1700 and the epicenter of the 27 February 2010 Chile earthquake. (b) Mainshock (red star) and aftershocks of the 2010 Chilean earthquake (gray dots) during one day since the mainshock occurred.

2. POST TSUNAMI FIELD SURVEY

(1) Logistics

Because the tsunami hit quite long extent of Chilean coast, the survey area needed to be prioritized. We decided to deploy the most severely affected area in Biobio region. The survey team was deployed along the central coast of Chile from 18 to 25 April 2010. **Fig.2** shows the route of the survey team. Setting the base lodging in Concepcion, we started the survey on 18 April from Talcahuano to visit eight coastal communities using a car.

(2) Methods

Conventionally, the post-tsunami survey measures tsunami inundation and run-up height, flow depth, and extent of inundation zone. The inundation height is measured as the height of watermarks on structures or debris on trees above sea level (after tide correction), and the run-up height as the altitude of the inland limit of tsunami penetration. Flow depth is the thickness of tsunami inundation flow measured as the height of the watermark from the local ground level. Measurements were conducted using the laser range finder (Laser Technology Inc.) with survey rods and digital cameras with GPS and compass. During the survey, we interviewed witnesses to collect the information of tsunami features (time of the tsunami arrival, polarity of the first wave, timing of maximum wave). In total, we obtained 155 points along the coast as the measurement of tsunami inundation and run-up heights, and flow depths. **Figs.** 3 and 4 show the longshore distribution of the measured tsunami heights and depths. The complete dataset is provided in Appendix. We made the tide correction for all the data by using tide table at Talcahuano.

Along with the field measurements, we used high-resolution optical satellite images to inspect the impact of tsunami disaster. **Table 1** is the list of high-resolution satellite images used in the inspection of tsunami-affected area.

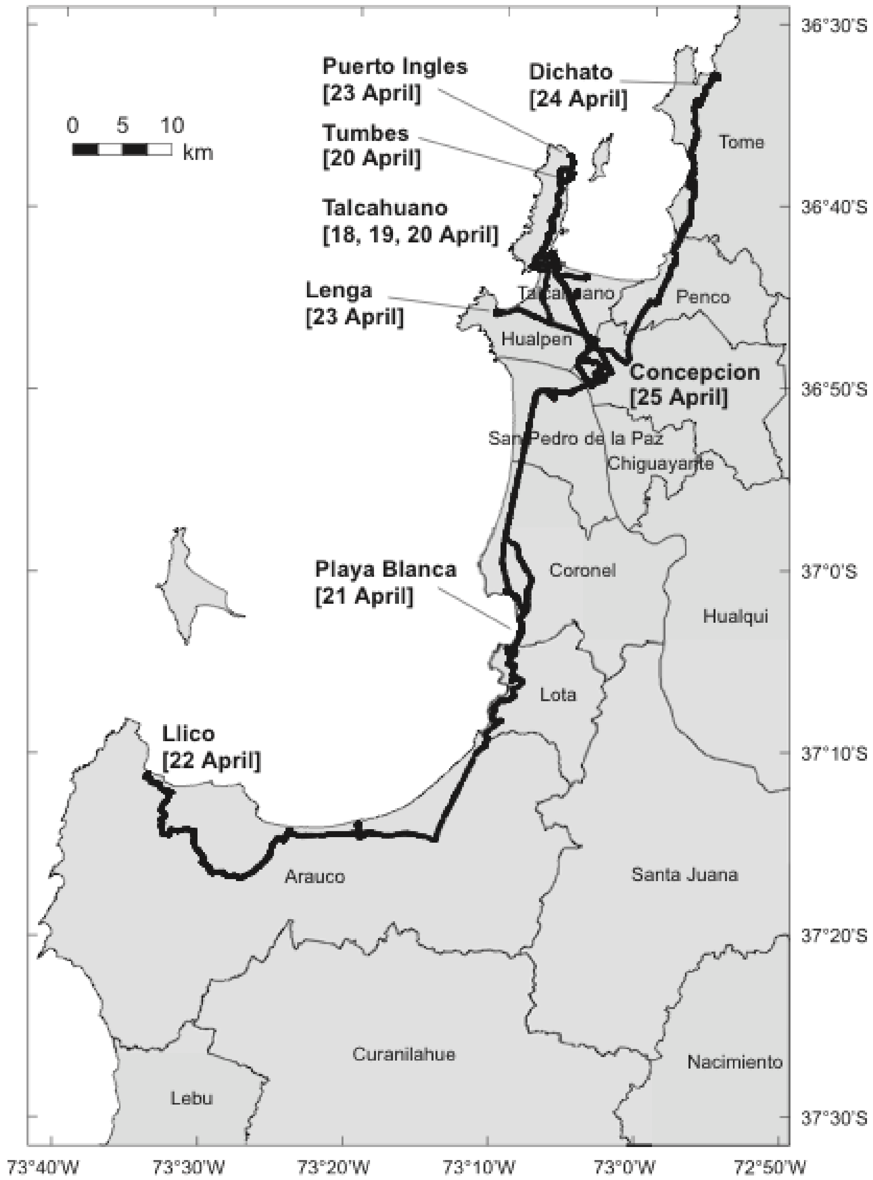

Fig. 2 The route and area of the post-tsunami field survey in Biobio region.

Table 1 Acquired satellite images for the use of inspection in the tsunami- affected area.

Acquired area	Sensor or [Source]	Acquisition date
Talcahuano	WorldView-2	6 March, 2010
Talcahuano	QuickBird [Google]	13 April, 2009
Dichato	QuickBird [Google]	5 March, 2010
Dichato	QuickBird [Google]	26 April, 2006
Llico	GeoEye-1 [Google]	8 October, 2009

3. RESULTS

(1) Talcahuano

Talcahuano is the port city in Biobio Region, which contains the naval base, and has approximately 250,000 inhabitants as a population (2002 census). According to the tide gauge record (NOAA, 2010), the first wave of tsunami reached Talcahuano at 3:30 (Local time) with receded wave. After the arrival of first wave, the tide gauge at Talcahuano did not successfully record the tsunami and stopped transmitting data. CATOE (Centro de Alertamiento Temprano y Oficina de Emergencia) reported that the tsunami attacked the coast at least four times with its period of 45 to 60 minutes, and the fourth wave was the largest.

Fig. 5 represents the result of tsunami inundation height measurement in Talcahuano. The tsunami penetrated approximately 300 m inland in the port-town area and more than 1 km in the southern coastal marsh. Tsunami inundation reached to 6-8 m in port-town area and 10 m in the coastal marsh. This figure also shows the comparison of pre and post event satellite images in Talcahuano port (**Figs.** 5(b), (c)). Significant amount of containers and fishing boats were left as tsunami debris, which caused long duration of failure of port and harbor facilities. While the tsunami left considerable damage to the town of Talcahuano (eastern bottom of the bay), no damage was found in the western port area (San Vicente). The measured tsunami run-up height in San Vicente was 3.4 m (**Fig.** 5(a)).

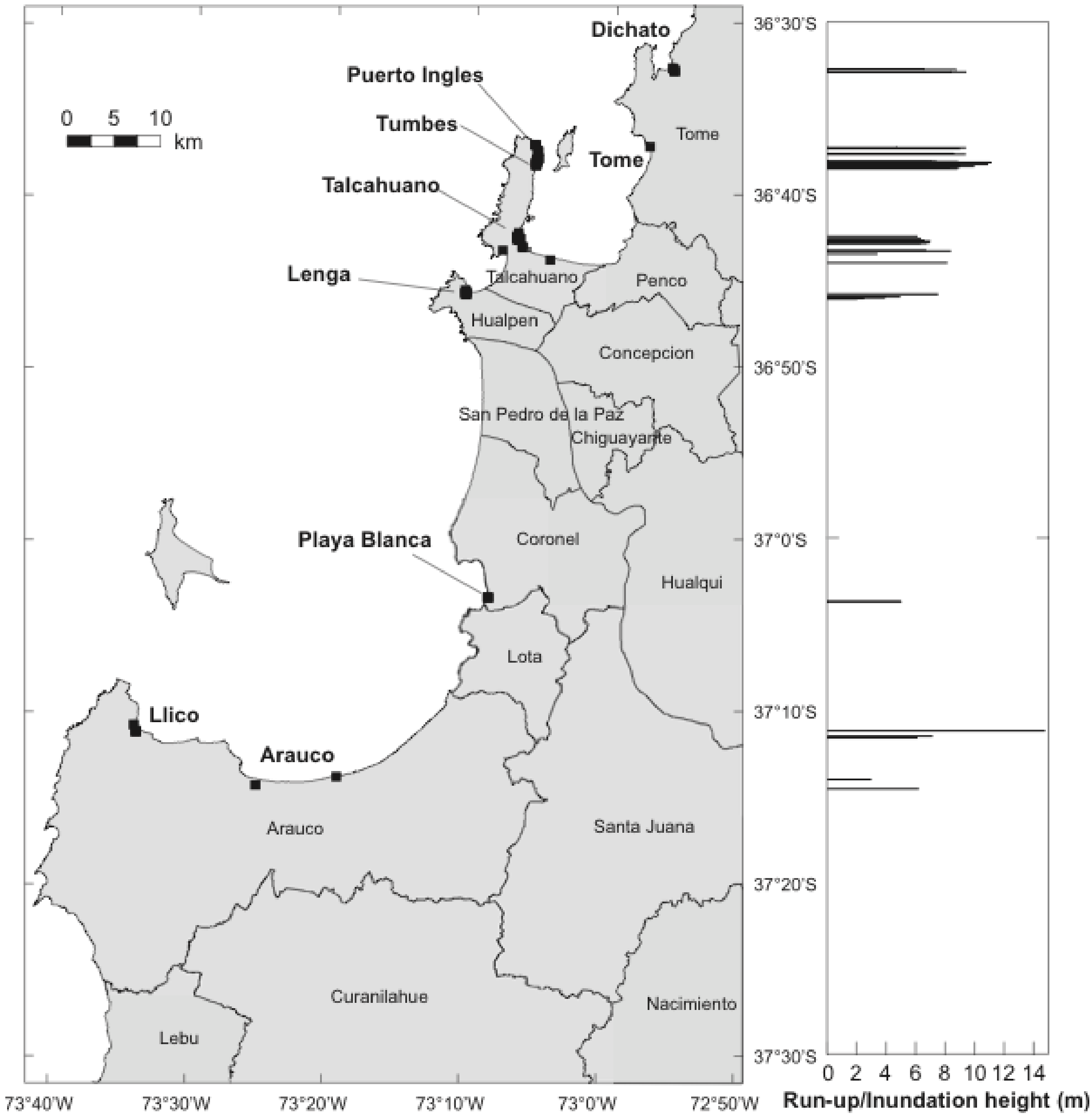

Fig.3 Longshore distribution of inundation and run-up height above the astronomical tide level when the tsunami arrived. Tide correction was made by using tide table in Talcahuano.

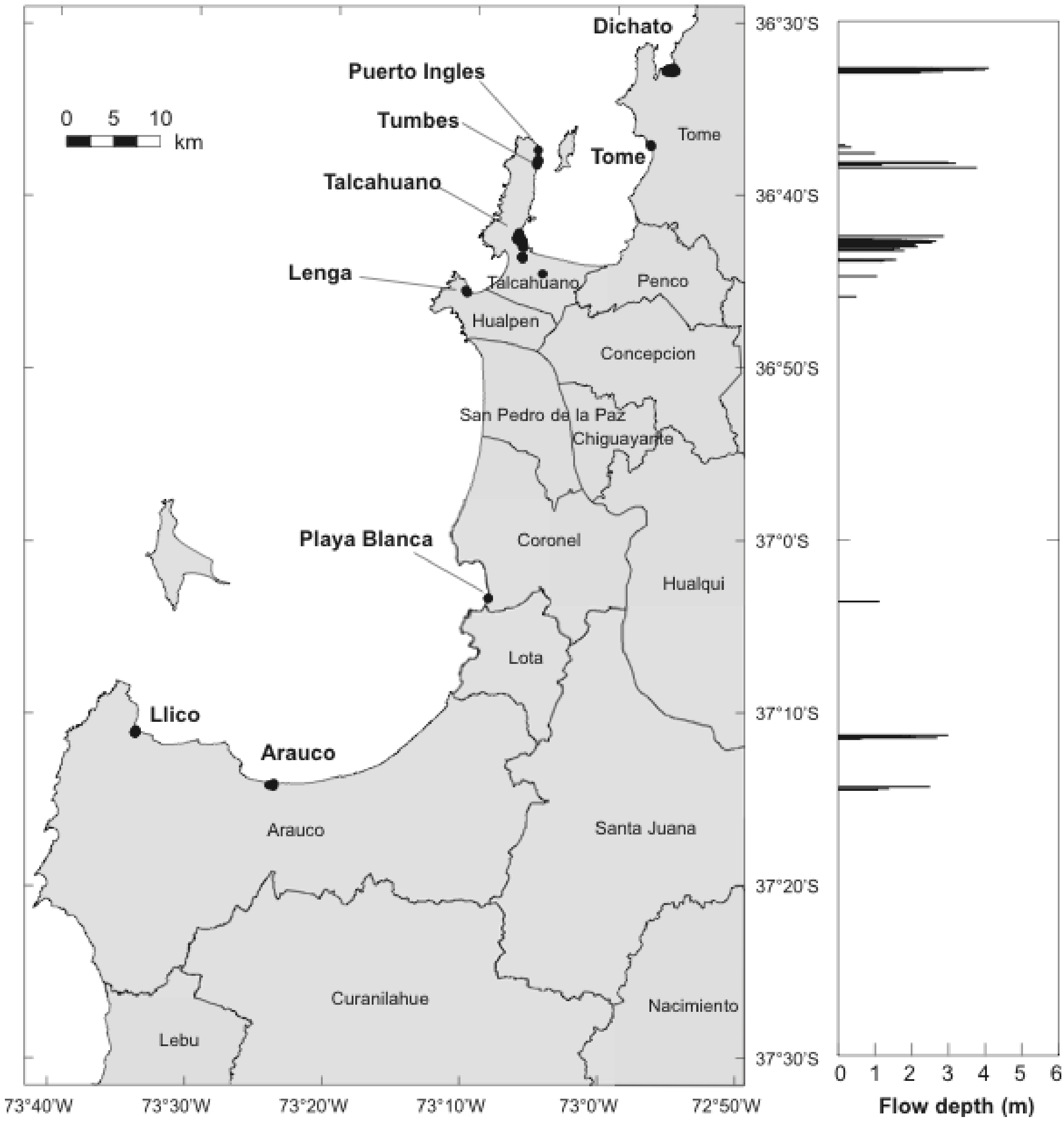

Fig.4 Longshore distribution of measured flow depths, which were measured as a height of watermark of tsunami penetration above the ground level.

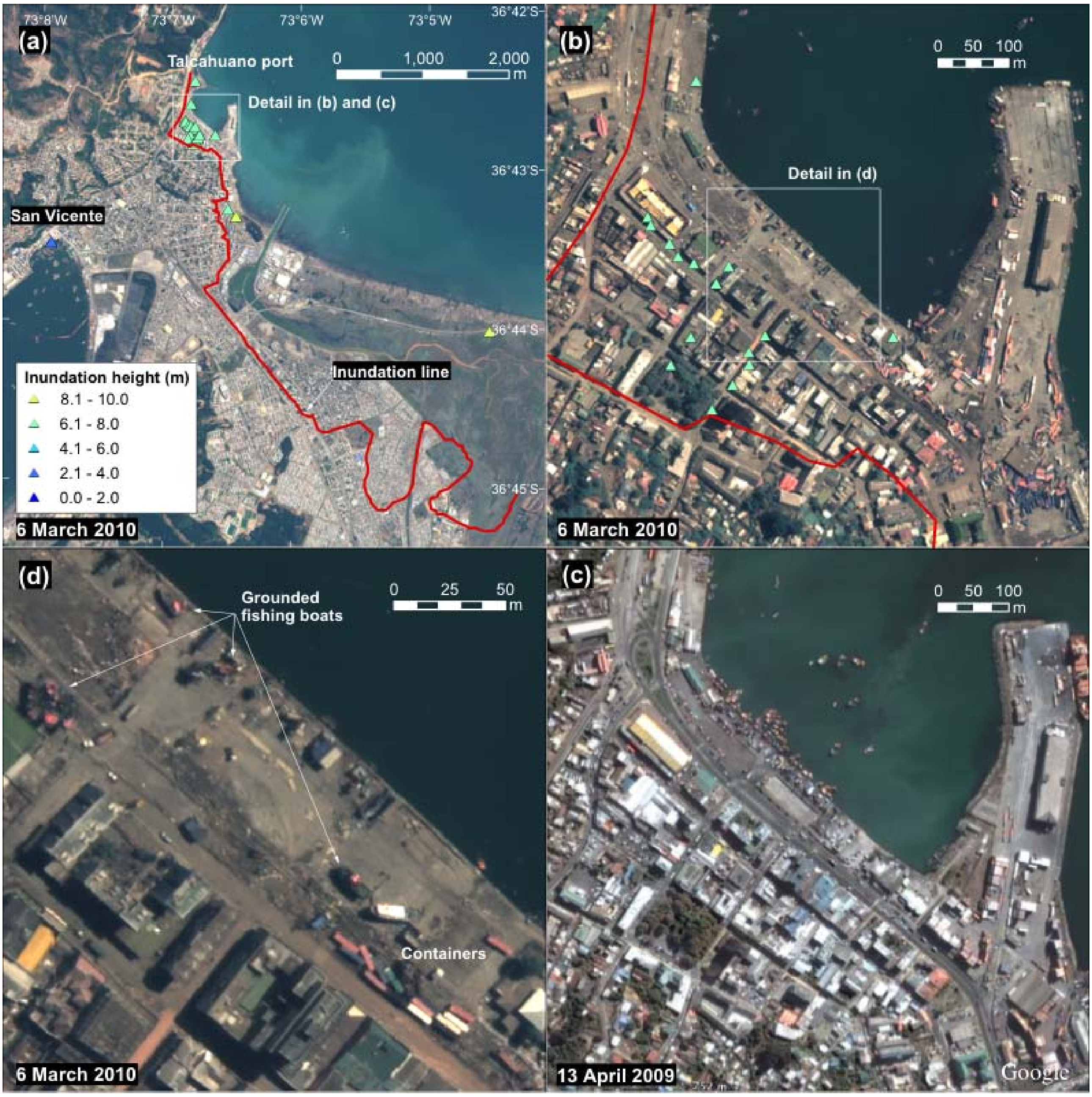

Fig. 5 (a) Result of tsunami height measurement in Talcahuano. The red line indicates the extent of inundation zone which was obtained by the interview with CATOE (Centro de Alertamiento Temprano y Oficina de Emergencia). (b) Damage in Talcahuano found in the post-event satellite image (WorldView-2). (c) Satellite image of Talcahuano before the tsunami attack (13 April 2009, from Google) (d) Close-up view of port of Talcahuano. Grounded fishing boats and drifted containers were seen.

Fig. 6 Result of tsunami flow depth measurement in the town of Talcahuano. The tsunami penetrated approximately 100 m inland with the flow depth of up to 2-3 m.

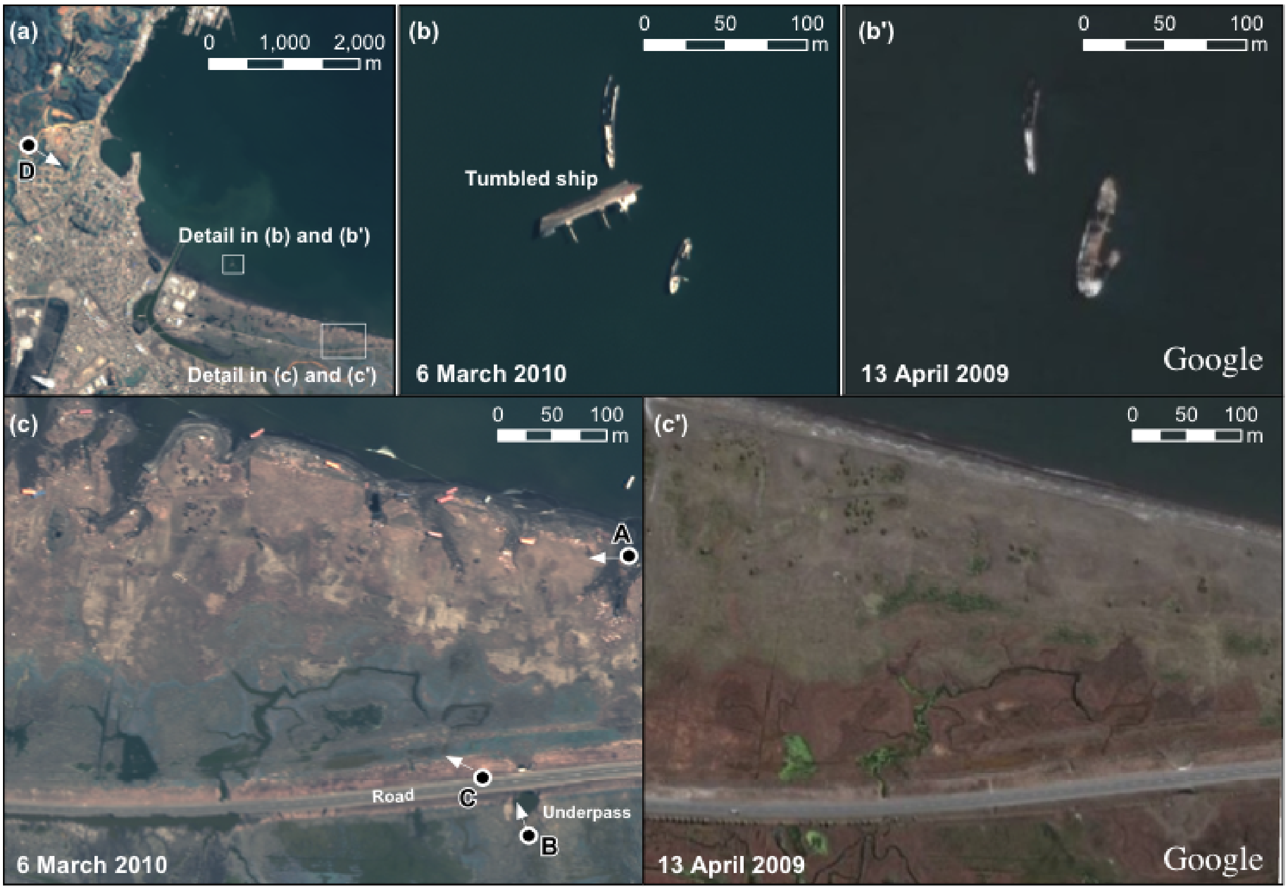

Fig. 7 Pre and post event satellite images in Talcahuano. Points A to D represent the position of ground photos taken by the authors (**Fig. 8**). White arrow is approximate direction of the camera focus. (a) Overview of Talcahuano port. (b) and (b') A 70m-long tumbled ship found the east of waterway. (c) and (c') Considerable change of coastline and drifted containers in the coastal marsh.

Fig. 8 Ground photos in Talcahuano taken by the authors. Each point is identified in **Fig. 7**. A : Tsunami debris and drifted containers in the coastal marsh. B : Erosion by the tsunami inundation found at the underpass. C : Overview of the coastal marsh inundated by the tsunami. D : Panoramic view of the coastal marsh from the hill.

According to the interview with eyewitness, the tsunami slightly overtopped the dock of the harbor but did not inundate out of the port. Possible causes of this discrepancy may be local effect of tsunami source mechanisms and the condition of harbor oscillation related to the size and shape of the bay.

In the town of Talcahuano, the tsunami penetrated with up to 2-3 m of flow depth (**Fig. 6**). After inspecting the structural damage in the town, some washed-away structures were found, but it was limited within the port facilities (north-west) and industrial area (south-west). Most of the structural damage in the town was likely to be caused by ground shaking, but minor damage, e.g. bending shutters of commercial buildings and broken windows.

(2) Inspection of satellite images

Inspecting pre and post event satellite images and ground photos helps to understand multi aspects of tsunami disaster. **Fig. 7** is the comparison of pre and post event satellite images in Talcahuano. We acquired the pre-tsunami image from GoogleEarth (QuickBird image taken on 13 April, 2009), and used WorldView-2 pan-sharpened composite image as post-tsunami image. From post-tsunami image and field survey, we found the tumbled ship at the west of waterway in Tulcahuano bay that has been stably stood in the bay (even though it was not in use). In the coastal marsh, considerable changes of shoreline and tsunami debris are seen in the satellite images, and it was found from the ground photos (**Fig. 8**) that the coastal sand were eroded by inland penetration of tsunami.

(3) Detection of salt-water penetration

Since salt-water penetration causes death of vegetation, sometimes it is used as a clear indicator of tsunami inundation. Using a specific feature of vegetation, i.e. strong absorption of visible red-band and strong reflection of nir-band, NDVI is defined by Equation (1) using the reflectance of near infrared and visible red bands.

$$\text{NDVI} = (\text{Near infrared} - \text{Red}) / (\text{Near infrared} + \text{Red}) \quad (1)$$

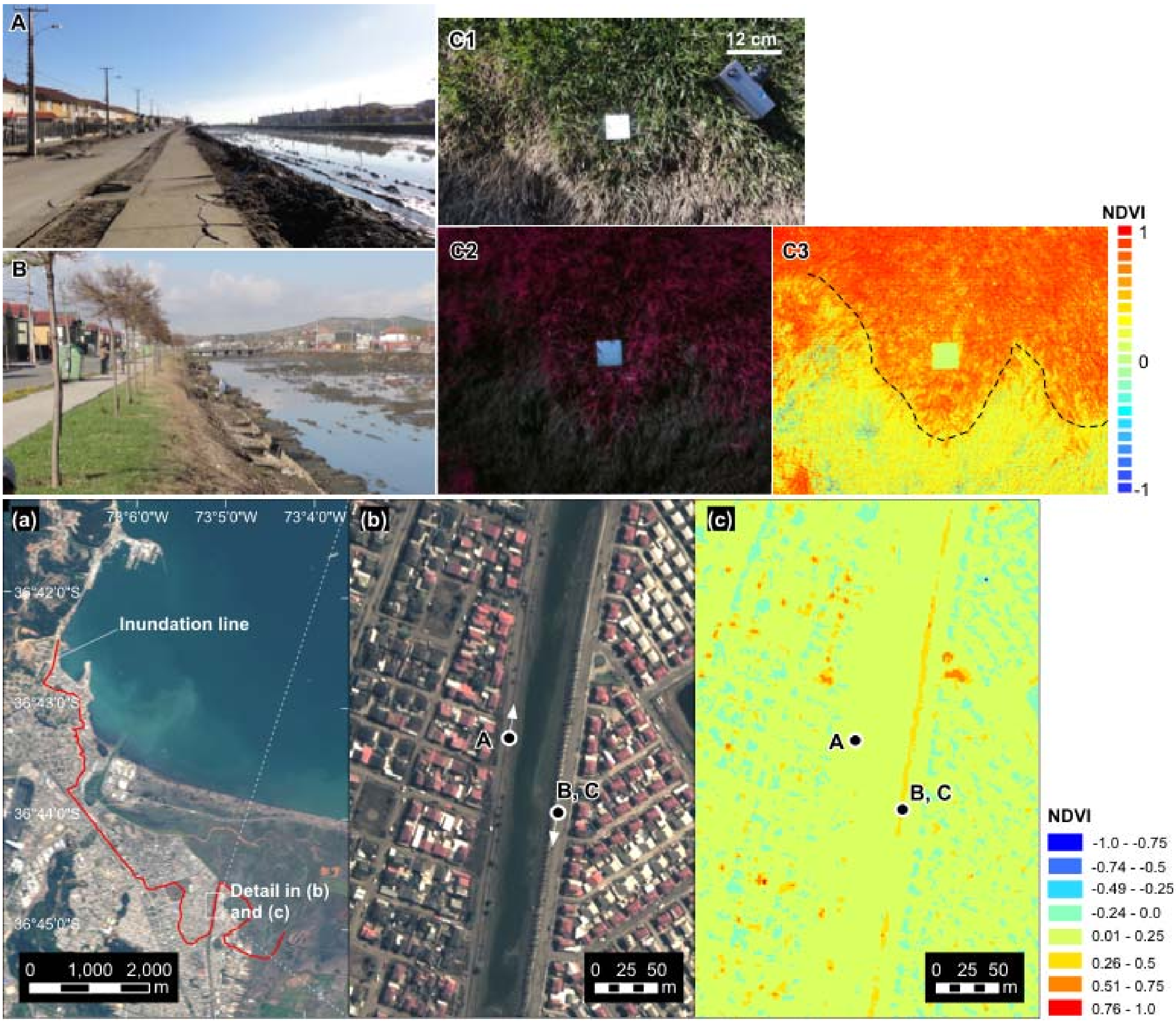

Fig. 9 (a) Inspection area of salt-water penetration, (b) Pan-sharpened multi-spectral image of WorldView-2 acquired on 6 March 2010. A, B and C is the point of ground photos, White arrow is approximate direction of camera focus. (c) Spatial distribution of NDVI Western. A and B : Ground photos taken on the western and eastern bank of the canal respectively. C1 is the ground photo for inspecting vegetation activity (Same position as B). C2 and C3 : False color composite image and NDVI taken by the multi spectral camera (Tetracam ADC3). White plate is the reflector used for calibration.

Here, we focused on the eastern bank of the canal in Talcahuano. **Fig. 9** indicates the area of investigation and illustrates the result of detecting tsunami penetration by the analysis of WorldView-2 pan-sharpened multi-spectral image and the multi spectral camera (Tetracam ADC3). As shown in the ground photos (**Figs. 9 A and B**), considerable inundation was found on the western bank of the canal while the eyewitness testified that the tsunami slightly overtopped the eastern bank (no inundation in houses). Using the multi spectral camera that takes visible red, green and near infrared bands, we first calculated NDVI at the top of the bank where the tsunami did not overtop (**Fig. 9B**). As a result, we found that NDVI of the dead vegetation becomes less than 0.3. Using the threshold value determined by the spectral camera, we discuss the salt-water penetration on the eastern bank of the canal. **Fig. 9 (c)** shows the distribution of NDVI calculated from the post-tsunami WorldView-2 image (pan-sharpened). NDVI indicates lower value on the western bank (inundated) while relatively higher value on eastern bank (not inundated), and these features are quite consistent with the ground photos A and B.

(4) Tumbes, Puerto Ingles and Llico

Tumbes locates and Puerto Ingles are the coastal communities, which were isolated by the limited road access. **Fig.10** represents the overview of tsunami height measurements. Tsunami attacked these communities with up to 11 m height and caused significant damage. Along the coast from Tumbes to Puerto Ingles, the tsunami was particularly devastating to demolish the houses of isolated villages (**Fig.11**). Some survivors mentioned that the first wave was withdrawal and the 2nd wave was the largest. Having the experience and lessons from the 1960 Chilean tsunami, most of the village people evacuated to the hill immediately after the ground shaking. They mentioned that the tsunami in 1960 was witnessed only as receded sea and did not cause inundation.

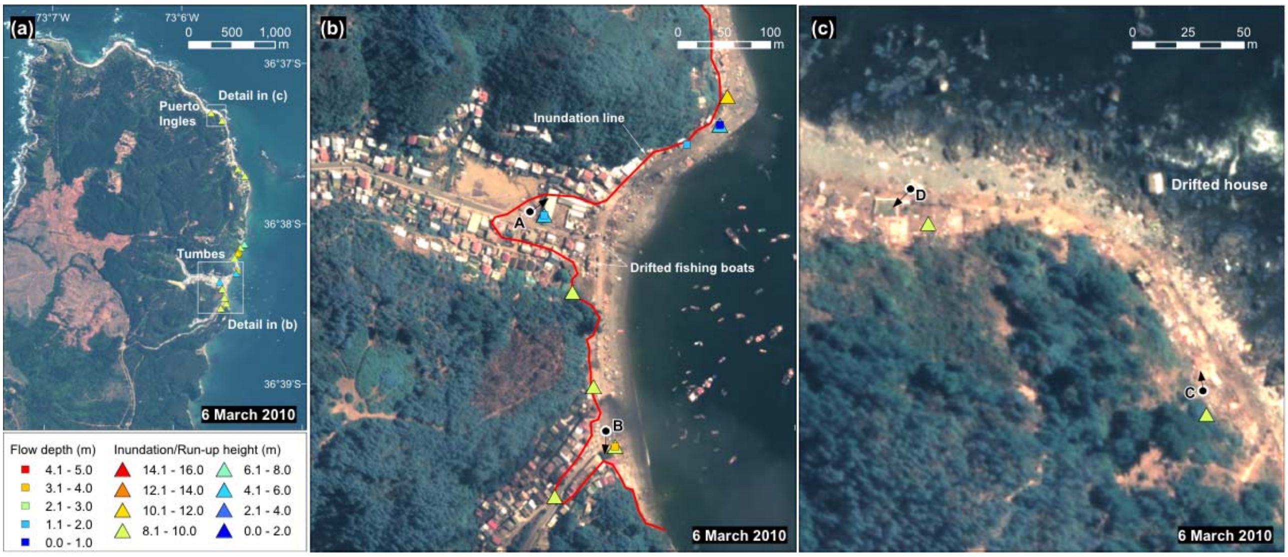

Fig. 10 (a) Overview of tsunami measurements (inundation and run-up heights) in Tumbes and Puerto Ingles. (b) Detailed features of the measurements and the damage in Tumbes. (c) Devastated damage in Puerto Ingles. Point A to D is the position of ground photos in **Fig. 11** respectively with the arrow of focus direction.

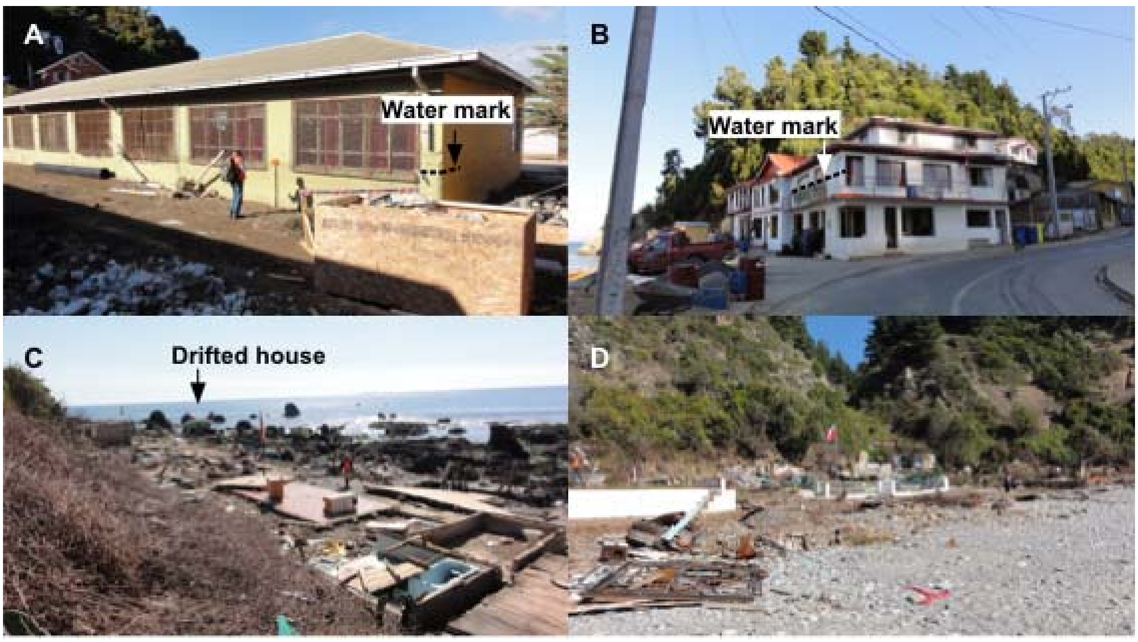

Fig. 11 Ground photos from Tumbes (A, B) and from Puerto Ingles (C, D). A : Watermark on school building. B : Watermark on the house of Tumbes, C and D : Completely devastated village of Puerto Ingles.

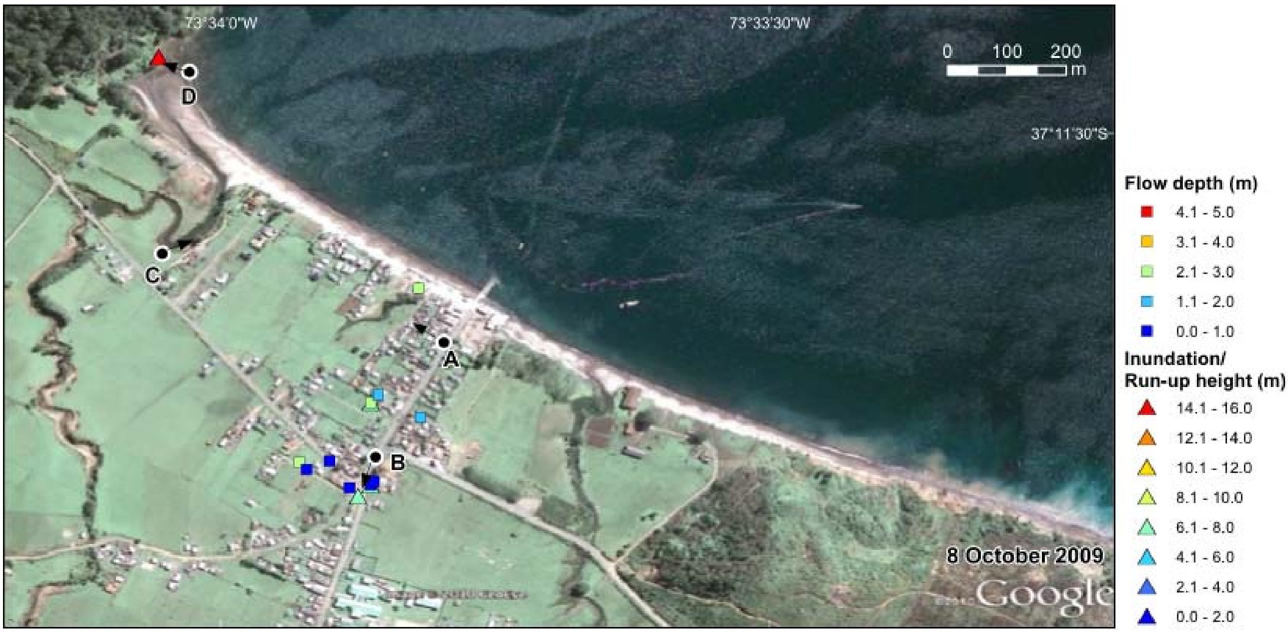

Fig 12. Result of tsunami height measurement in Llico. Point A to D are the position of ground photos with the arrow of focus direction shown in **Fig. 13**.

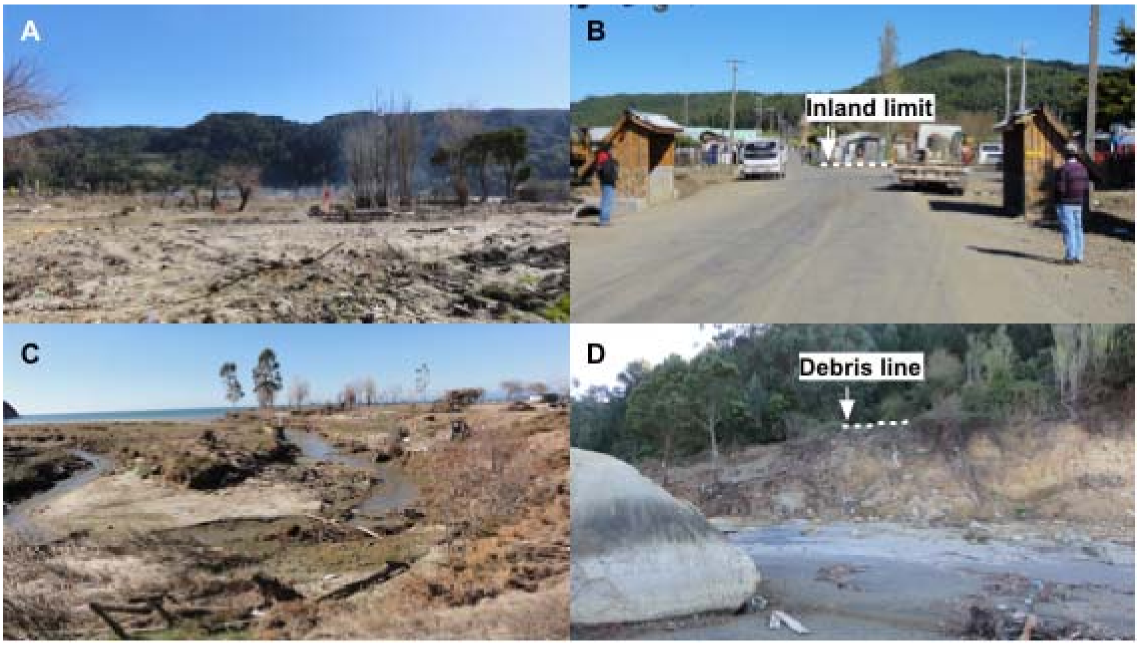

Fig. 13 Ground photos from Llico. A : Completely devastated village. In the village, there were around 60 houses before tsunami. Almost all the houses were washed-away. B : Inland limit of tsunami inundation that is approximately 400 m from the shoreline. C : Tsunami run-up along the river. D : Tsunami debris line above 14.8 m pre-tsunami sea level.

(5) Dichato

Dichato is a coastal village of approximately 3,000 inhabitants (Census 2002), which belongs to the municipality of Tome, located 37 km north of the city of Concepcion. Having a beautiful sandy beach, Dichato was very popular in summer for water sports and recreation. Attacked by the tsunami, Dichato became one of the most devastated towns. According to Dichato-Tome Emergency office, 405 families living in camps, and 1223 families were affected on their properties **Fig. 14** represents the measured tsunami run-up height and flow depths. The tsunami penetrated approximately 800 m inland to 10 m altitude. **Figs. 15 and 16** illustrates the devastating damage in Dichato. In this area, most of the houses were washed away and the tsunami left considerable amount of debris. According to the eyewitness who watched the tsunami from 8-story building, the first wave of tsunami hit at 5:00 (AM) after most of the people evacuated. In addition, he said that the tsunami attack was at least 3 times and the 3rd wave was the largest. The other eyewitness said that the tsunami did not come first from the sea, but from the backside with not so much power (first wave).

Number of fatality and missing reported is 66 and the surviving resident believe that most of the victims are not from Dichato but tourists or different regions, also heart attack elders or drunken people. This is mainly because the residents of Dichato knew about the possible tsunami after the earthquake and had evacuation drills.

6. SUMMARY

In summary, the results of our survey provide a dataset of tsunami run-up and inundation heights, flow depths and extent of inundation at approximately 150 points. The survey extent was from Dichato to Llico, the areas mostly devastated by the tsunami. The tsunami inundation heights and flow depths were well recorded and will be used as a constraint in developing tsunami source model to comprehend the features of tsunami propagation and coastal inundation. Also, we collected the eyewitness accounts to describe the picture of tsunami attack. Most of the eyewitnesses said that the largest tsunami did not occur in the first wave.

Throughout the trip, we found that many of survivors knew the past event 1960 and evacuated immediately after the ground shaking. Again we found that education and passing the lessons from the past event is highly valued to mitigate the tsunami fatalities.

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Fig. 14 Tsunami height, flow depth and extent of inundation in Dichato.

Fig. 15 Pre and post event satellite images of the most devastated area in Dichato. Points A to G represent the position of ground photos taken by the authors (**Fig. 16**). White arrow is approximate direction of the camera focus.

Fig. 16 Ground photos from Dichato. A and B : Most devastated area. Only the unit of bathroom is remained. C : Damage on a bridge and erosion by tsunami inundation. D: Withstanding house, but significant damage. E : Drifted boat. F : Watermark on the house (approximately 2 m of flow depth). G : Panoramic view of the town of Dichato.

APPENDIX A Tsunami measurement data

Attribution : I : inundation height/depth, R : run-up height

Point Number	ID	Place	Latitude [dd]	Longitude [dd]	Attribu-tion	Depth [m]	Height [m]
1	JST-CRIEPI-1	Talcahuano	-36.712167	-73.114861	I	2.30	6.52
2	JST-CRIEPI-2	Talcahuano	-36.712500	-73.114500	I	2.44	6.58
3	JST-CRIEPI-3	Talcahuano	-36.712278	-73.114806	I	2.29	6.54
4	JST-CRIEPI-4	Talcahuano	-36.712667	-73.114361	I	2.34	6.53
5	JST-CRIEPI-5	Talcahuano	-36.712750	-73.114111	I	2.34	6.43
6	JST-CRIEPI-6	Talcahuano	-36.713000	-73.113750	I	2.35	6.61
7	JST-CRIEPI-7	Talcahuano	-36.713694	-73.114139	I	1.27	6.59
8	JST-CRIEPI-8	Talcahuano	-36.714056	-73.114444	I	0.74	6.25
9	JST-CRIEPI-9	Talcahuano	-36.712778	-73.113556	I	2.67	7.03
10	JST-CRIEPI-10	Talcahuano	-36.733583	-73.074778	R	-	8.16
11	JST-CRIEPI-11	Talcahuano	-36.721333	-73.109056	I	1.53	6.72
12	JST-CRIEPI-12	Talcahuano	-36.707970	-73.113667	I	2.88	6.13
13	JST-CRIEPI-13	Talcahuano	-36.710417	-73.114133	I	0.95	6.35
14	JST-CRIEPI-14	Talcahuano	-36.714613	-73.113778	R	0.09	6.37
15	JST-CRIEPI-15	Talcahuano	-36.714299	-73.113456	I	1.80	6.73
16	JST-CRIEPI-16	Talcahuano	-36.714028	-73.113197	I	1.72	6.92
17	JST-CRIEPI-17	Talcahuano	-36.713872	-73.113211	I	1.66	6.96
18	JST-CRIEPI-18	Talcahuano	-36.713654	-73.112961	I	2.15	6.90
19	JST-CRIEPI-19	Talcahuano	-36.713643	-73.110922	I	2.48	6.70
20	JST-CRIEPI-20	Talcahuano	-36.713600	-73.112130	I	2.52	-
21	JST-CRIEPI-21	Talcahuano	-36.713600	-73.112130	I	1.45	-
22	JST-CRIEPI-22	Talcahuano	-36.714070	-73.110450	I	2.55	-
23	JST-CRIEPI-23	Talcahuano	-36.714840	-73.110650	I	1.81	-
24	JST-CRIEPI-24	Talcahuano	-36.715120	-73.110740	I	1.67	-
25	JST-CRIEPI-25	Talcahuano	-36.715240	-73.110790	I	0.92	-
26	JST-CRIEPI-26	Talcahuano	-36.715160	-73.111270	I	0.33	-
27	JST-CRIEPI-27	Talcahuano	-36.714830	-73.111250	I	1.49	-
28	JST-CRIEPI-28	Talcahuano	-36.714440	-73.111610	I	1.59	-
29	JST-CRIEPI-29	Talcahuano	-36.714210	-73.112070	I	1.73	-
30	JST-CRIEPI-30	Talcahuano	-36.713980	-73.112530	I	2.09	-
31	JST-CRIEPI-31	Talcahuano	-36.713560	-73.113080	I	1.94	-
32	JST-CRIEPI-32	Talcahuano	-36.713020	-73.113530	I	2.19	-
33	JST-CRIEPI-33	Talcahuano	-36.712800	-73.114060	I	2.33	-
34	JST-CRIEPI-34	Talcahuano	-36.712230	-73.113890	I	1.87	-
35	JST-CRIEPI-35	Talcahuano	-36.711660	-73.114730	I	1.70	-
36	JST-CRIEPI-36	Talcahuano	-36.712230	-73.114920	I	2.46	-
37	JST-CRIEPI-37	Talcahuano	-36.712680	-73.114400	I	2.49	-
38	JST-CRIEPI-38	Talcahuano	-36.713770	-73.114150	I	1.50	-
39	JST-CRIEPI-39	Talcahuano	-36.714090	-73.113990	I	1.15	-
40	JST-CRIEPI-40	Talcahuano	-36.714640	-73.112920	I	0.41	-
41	JST-CRIEPI-41	Talcahuano	-36.714090	-73.114380	I	0.79	-
42	JST-CRIEPI-42	Talcahuano	-36.714470	-73.114760	I	0.30	-
43	JST-CRIEPI-43	Talcahuano	-36.713860	-73.115880	I	0.66	-
44	JST-CRIEPI-44	Talcahuano	-36.713540	-73.115640	I	1.07	-
45	JST-CRIEPI-45	Talcahuano	-36.712790	-73.115410	I	1.22	-
46	JST-CRIEPI-46	Talcahuano	-36.712040	-73.115270	I	1.85	-
47	JST-CRIEPI-47	Tumbes	-36.640278	-73.094083	R	-	10.00
48	JST-CRIEPI-48	Tumbes	-36.639528	-73.094444	I	1.20	5.34
49	JST-CRIEPI-49	Tumbes	-36.641778	-73.093528	I	3.77	8.28
50	JST-CRIEPI-50	Tumbes	-36.642278	-73.094250	R	-	8.87

51	JST-CRIEPI-51	Tumbes	-36.641194	-73.093806	R	-	8.97
52	JST-CRIEPI-52	Talcahuano	-36.722083	-73.107972	I	1.80	8.41
53	JST-CRIEPI-53	Tumbes	-36.636269	-73.092089	R	-	6.83
54	JST-CRIEPI-54	Tumbes	-36.635472	-73.091417	R	-	7.45
55	JST-CRIEPI-55	Tumbes	-36.635583	-73.091389	R	-	7.03
56	JST-CRIEPI-56	Tumbes	-36.635944	-73.091861	R	-	8.90
57	JST-CRIEPI-57	Tumbes	-36.636378	-73.092119	R	-	11.04
58	JST-CRIEPI-58	Tumbes	-36.636539	-73.092194	R	-	11.12
59	JST-CRIEPI-59	Tumbes	-36.637019	-73.092583	R	-	8.96
60	JST-CRIEPI-60	Tumbes	-36.638336	-73.092253	R	-	10.90
61	JST-CRIEPI-61	Tumbes	-36.638617	-73.092336	I	0.32	5.40
62	JST-CRIEPI-62	San Marcos	-36.746880	-73.084256	I	1.06	-
63	JST-CRIEPI-63	Tumbes	-36.636580	-73.092170	I	3.00	-
64	JST-CRIEPI-64	Tumbes	-36.637400	-73.092380	I	3.20	-
65	JST-CRIEPI-65	Tumbes	-36.638810	-73.092730	I	1.15	-
66	JST-CRIEPI-66	Playa Blanca	-37.061389	-73.141944	I	1.10	5.00
67	JST-CRIEPI-67	Playa Blanca	-37.061889	-73.141389	R	-	5.06
68	JST-CRIEPI-68	Playa Blanca	-37.061450	-73.142070	I	1.10	
69	JST-CRIEPI-69	Arauco	-37.237611	-73.321389	R	-	3.01
70	JST-CRIEPI-70	Llico	-37.197167	-73.564583	R	-	6.14
71	JST-CRIEPI-71	Llico	-37.197000	-73.564389	I	0.60	6.10
72	JST-CRIEPI-72	Llico	-37.195750	-73.564389	I	2.12	7.17
73	JST-CRIEPI-73	Curaquilla	-37.246806	-73.418917	R	-	6.22
74	JST-CRIEPI-74	Llico	-37.190528	-73.566944	R	-	14.78
75	JST-CRIEPI-75	Llico	-37.194020	-73.563660	I	3.00	-
76	JST-CRIEPI-76	Llico	-37.196660	-73.565470	I	2.70	-
77	JST-CRIEPI-77	Llico	-37.196640	-73.565010	I	0.67	-
78	JST-CRIEPI-78	Llico	-37.196770	-73.565360	I	0.61	-
79	JST-CRIEPI-79	Llico	-37.197050	-73.564710	I	0.60	-
80	JST-CRIEPI-80	Llico	-37.196950	-73.564340	I	0.53	-
81	JST-CRIEPI-81	Llico	-37.195980	-73.563630	I	1.70	-
82	JST-CRIEPI-82	Llico	-37.195640	-73.564270	I	1.96	-
83	JST-CRIEPI-83	Curaquilla	-37.245660	-73.401740	I	1.40	-
84	JST-CRIEPI-84	Curaquilla	-37.243910	-73.396810	I	2.50	-
85	JST-CRIEPI-85	Curaquilla	-37.246780	-73.397450	I	1.08	-
86	JST-CRIEPI-86	Candelaria	-36.628500	-73.091472	R	-	9.39
87	JST-CRIEPI-87	Cantera	-36.627758	-73.092372	I	1.00	8.60
88	JST-CRIEPI-88	Puerto Ingles	-36.622778	-73.094556	R	-	9.04
89	JST-CRIEPI-89	Puerto Ingles	-36.622028	-73.095972	R	-	9.41
90	JST-CRIEPI-90	San Vicente	-36.725111	-73.131944	R	-	3.41
91	JST-CRIEPI-91	Lenga	-36.766361	-73.173972	I	0.50	4.98
92	JST-CRIEPI-92	Lenga	-36.768361	-73.174833	R	-	2.06
93	JST-CRIEPI-93	Lenga	-36.768028	-73.175639	R	-	2.52
94	JST-CRIEPI-94	Lenga	-36.767333	-73.176389	R	-	3.94
95	JST-CRIEPI-95	Lenga	-36.764083	-73.175639	R		7.54
96	JST-CRIEPI-96	Tome	-36.622111	-72.957528	I	0.35	4.76
97	JST-CRIEPI-97	Dichato	-36.548583	-72.930028	R	-	9.44
98	JST-CRIEPI-98	Dichato	-36.548417	-72.930306	I	2.00	8.44
99	JST-CRIEPI-99	Dichato	-36.546194	-72.930806	R	-	8.79
100	JST-CRIEPI-100	Dichato	-36.545583	-72.932500	I	4.10	6.56
101	JST-CRIEPI-101	Dichato	-36.547306	-72.939278	I	3.71	-
102	JST-CRIEPI-102	Dichato	-36.547306	-72.939278	I	1.87	-
103	JST-CRIEPI-103	Dichato	-36.547472	-72.939306	I	1.75	-
104	JST-CRIEPI-104	Dichato	-36.547583	-72.940361	I	1.80	-

105	JST-CRIEPI-105	Dichato	-36.548028	-72.940028	I	1.78	-
106	JST-CRIEPI-106	Dichato	-36.548472	-72.941139	I	2.55	-
107	JST-CRIEPI-107	Dichato	-36.548750	-72.941333	I	1.03	-
108	JST-CRIEPI-108	Dichato	-36.548639	-72.939528	I	2.85	-
109	JST-CRIEPI-109	Dichato	-36.548639	-72.939222	I	0.58	-
110	JST-CRIEPI-110	Dichato	-36.548333	-72.939222	I	1.96	-
111	JST-CRIEPI-111	Dichato	-36.548028	-72.938667	I	1.48	-
112	JST-CRIEPI-112	Dichato	-36.548222	-72.938361	I	1.97	-
113	JST-CRIEPI-113	Dichato	-36.548680	-72.937080	I	1.22	-
114	JST-CRIEPI-114	Dichato	-36.548370	-72.936070	I	1.01	-
115	JST-CRIEPI-115	Dichato	-36.547950	-72.935530	I	1.95	-
116	JST-CRIEPI-116	Dichato	-36.547730	-72.935030	I	2.38	-
117	JST-CRIEPI-117	Dichato	-36.547620	-72.934890	I	2.05	-
118	JST-CRIEPI-118	Dichato	-36.547050	-72.934420	I	4.00	-
119	JST-CRIEPI-119	Dichato	-36.546490	-72.934220	I	2.73	-
120	JST-CRIEPI-120	Dichato	-36.545800	-72.934430	I	2.12	-
121	JST-CRIEPI-121	Dichato	-36.545890	-72.934510	I	2.54	-
122	JST-1	Talcahuano	-36.731702	-73.108907	I	0.68	-
123	JST-2	Talcahuano	-36.732127	-73.108920	I	1.26	-
124	JST-3	Talcahuano	-36.732127	-73.108920	I	1.18	-
125	JST-4	Talcahuano	-36.731015	-73.109097	I	1.59	-
126	JST-5	Talcahuano	-36.730803	-73.109310	I	1.48	-
127	JST-6	Talcahuano	-36.718993	-73.108610	I	1.68	-
128	JST-7	Talcahuano	-36.718207	-73.108715	I	1.51	-
129	JST-8	Talcahuano	-36.718072	-73.108925	I	2.17	-
130	JST-9	Talcahuano	-36.717693	-73.109075	I	1.52	-
131	JST-10	Talcahuano	-36.717687	-73.109215	I	1.78	-
132	JST-11	Talcahuano	-36.716822	-73.109195	I	1.53	-
133	JST-12	Talcahuano	-36.716688	-73.109030	I	2.12	-
134	JST-13	Talcahuano	-36.716688	-73.109030	I	1.70	-
135	JST-14	Talcahuano	-36.716722	-73.109058	I	2.05	-
136	JST-15	Talcahuano	-36.716722	-73.109058	I	1.60	-
137	JST-16	Talcahuano	-36.716720	-73.109107	I	2.00	-
138	JST-17	Talcahuano	-36.716770	-73.109397	I	1.98	-
139	JST-18	Talcahuano	-36.716805	-73.109702	I	2.03	-
140	JST-19	Talcahuano	-36.717238	-73.109867	I	1.32	-
141	JST-20	Talcahuano	-36.717415	-73.109757	I	0.55	-
142	JST-21	Tome	-36.619962	-72.958023	I	0.20	-
143	JST-22	Dichato	-36.549433	-72.934448	I	1.76	-
144	JST-23	Dichato	-36.549782	-72.933927	I	2.24	-
145	JST-24	Dichato	-36.548377	-72.930255	I	1.94	-
146	JST-25	Dichato	-36.548117	-72.938658	I	1.48	-
147	JST-26	Constitucion	-35.328178	-72.410415	I	1.13	-
148	JST-27	Constitucion	-35.328078	-72.410192	I	1.12	-
149	JST-28	Constitucion	-35.331180	-72.408433	I	0.89	-
150	JST-29	Constitucion	-35.331378	-72.408313	I	0.89	-
151	JST-30	Constitucion	-35.328343	-72.407100	I	1.83	-
152	JST-31	Constitucion	-35.328510	-72.407483	I	2.33	-
153	JST-32	Constitucion	-35.328467	-72.407605	I	2.35	-
154	JST-33	Constitucion	-35.324527	-72.410187	I	2.00	-
155	JST-34	Constitucion	-35.324703	-72.410562	I	2.20	-

Damage Investigation of the 2010 Chile Earthquake and Tsunami - Consideration to the Damage of a Structure subjected to a Seismic Excitation and a Following Tsunami Wave Load -

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We show the investigation results on the tsunami-induced damage of houses and infrastructures after subjected to a seismic excitation in the 2010 Chile earthquake and tsunami, from the field survey from 26 April to 3 May, 2010 for the affected areas.

Key Words : *2010 Chile earthquake and tsunami, damage of houses and infrastructures, combination of seismic and tsunami wave loads*

1. INTRODUCTION

The tsunami-induced damage of houses and infrastructures after subjected to a seismic excitation is observed in affected areas by the 2010 Chile earthquake and tsunami. Reports on the related damage have not been shown sufficiently enough for previous earthquake and tsunami disasters, although we can guess easily that there existed many houses and infrastructures suffered by combination of seismic and tsunami wave loads. From the reason above we focused on field survey to investigate the tsunami-induced damage of houses and infrastructures after subjected to a seismic excitation in the 2010 Chile earthquake and tsunami. This investigation was carried out based on the framework of research project on "Enhancement of earthquake and tsunami disaster mitigation technology in Peru" sponsored by the JST- JICA SATREPS project (leader, Professor F. Yamazaki at Chiba University) [1)].

2. DAMAGE OF HOUSES AND INFRASTRUCTURES

(1) Survey areas

The following tsunami-induced damage of houses and infrastructures after subjected to a seismic excitation is observed obviously in two areas: first area is the east part of Talcahuano and second one is Coliumu which is located at the opposite shore of Dichato (**Fig. 1**). In the former area the damage of a bridge, sewerage pipelines and houses is shown and in the latter area the damage of houses is shown (**Fig. 2**).

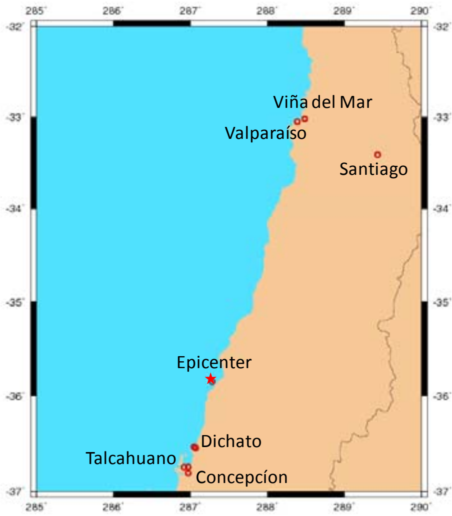

Fig.1 Subject areas in the related regions with the 2010 Chile earthquake.

Fig.2 Locations of the occurrence of the damage (left figure shows the locations at the east part of Talcahuano and right one at Coliumu).

(2) Damage of a bridge

Figure 3 show the damage of a bridge at the east part of Talcahuano. The bridge is located at the river mouth and it is a six-spanned bridge with prestressed concrete girders. The span length is about 10m long and the total width of a deck is about 20m long. Significant liquefaction occurs along both riversides in the direction from the location of the bridge to the 30m - 50m upstream. Consequently, subsidence of both abutments and these backfill occurs although we can not observe significant physical damage of bridge girders and piers. We guess that severer subsidence of the abutment at the left bank of the river by scouring of the backfill subjected to tsunami compression and tensile waves, follows the subsidence by the liquefaction subjected to ground motions, than that at the right bank.

Fig.3 Damage of a bridge

Fig.4 Damage of sewerage systems

(3) Damage of sewerage pipelines

Figure 4 show the damage of sewerage systems buried in adjacent road with the river at the east part of Talcahuano. Manholes of the systems are uplifted about 15cm to 25cm high from the road surface, and subsidence of buried pipelines and gaps between those spans occur at the side of the road in front of houses. It is inferred from the damage above that liquefaction of the ground with sewerage systems subjected to a ground shaking is a dominant influence factor of the damage. In addition to this, the tsunami-induced flow runs extensively into the suffered sewerage pipelines by the liquefaction, and causes the interruption of flowing of wastewater through the pipelines.

(4) Damage of houses at the east part of Talcahuano

Figure 5 show the damage of houses at the east part of Talcahuano, which are RC masonry ones.

The house in the upper part of **Fig. 5** seems to be suffered by about 1m inundation after the occurrence of subsidence and declination equivalent to about 40cm to 50cm height of the house due to ground motions. The subsidence and declination cause dominant shear crack between bricks and motor in the sidewall of the house. We can measure the inundation height at the site by the inundation horizontal marks remained in the 1st floor of the house.

Similarly, the house in the lower part of **Fig. 5** seems to be suffered by about 20cm subsidence of the ground, which is due to the liquefaction of surrounding soil subjected to ground motions. Consequently, it causes that the RC-framed beam is pulled down locally about 40cm at the joint corner between a column and a beam. The failure of the upper beam causes the failure of the sidewall in the house. These structural damage of the house is due to the forced displacement due to the liquefaction.

It is inferred that the houses in the areas are subjected more dominantly to the forced displacement due to the liquefaction, than to the inundation after the tsunami run-up along the river.

Fig.5 Damage of houses at the east part of Talcahuano

(5) Damage of houses at Coliumu

The houses in the areas at Coliumu, which is located at the opposite shore of Dichato, seem to be suffered by combination of forced vibration due to ground motions and direct tsunami wave pressure due to tsunami wave propagation. The structural type of houses suffered by the combination loads is a RC masonry one.

Figure 6 show the damage of the house by the combination loads. The minor horizontal cracks in the sidewall of the house occur at the height from the bottom of the wall to about 1m high, and furthermore the major one crack occurs in the diagonal direction from the joint corner between upper beam and a column. The former cracks seem to be due to the forced vibration of the house subjected to ground motions and the latter crack seems to be due to the tsunami wave pressure, which is modeled as a triangle load to a wall located in parallel with the direction of tsunami wave propagation [2), 3)]. Based on the results by previous research [2),3)], the occurrence of above diagonal major crack in the wall can be explained by the loading to a wall of tsunami wave pressure with a 3m - 4m inundation height.

Figure 7 show the damage of the house, which is suffered by no damage by ground motions, however is suffered by minor functional damage by tsunami inundation. Functional damage means that the residents can not use their own house for dairy life due to the inundation although the house is not suffered by the physical damage due to the combination of seismic and tsunami loads. One of residents says that the inundation reaches the height of the upper beam at the second floor of the house. It is inferred from his evidence that the inundation height at the house is about 7m - 8m from the ground level, which can be interpreted as very high inundation height to a house. The guideline on the tsunami-proof design for a building offered by Japanese Cabinet Office [4] describes how to design a building resisting the tsunami wave load of about 8m inundation height. The damage of this house should be further analyzed based on the evaluation framework of a tsunami wave load to a structural component by the guideline.

Fig.6 Damage of a house by combination of seismic and tsunami wave loads at Coliumu

Fig.7 Minor functional damage of a house by combination of seismic and tsunami wave loads at Coliumu

3. CONCLUDING REMARKS

We focused on field survey to investigate the tsunami-induced damage of houses and infrastructures after subjected to a seismic excitation in the 2010 Chile earthquake and tsunami. The following tsunami-induced damage of houses and infrastructures after subjected to ground motions is observed obviously in two areas: first area is the east part of Talcahuano and second one is Coliumu which is located at the opposite shore of Dichato. In the former area the damage of a bridge, sewerage pipelines and houses is shown and in the latter area the damage of houses is shown. The former damage of a bridge, sewerage pipelines and houses in the areas seems to be subjected more dominantly to the forced displacement due to the liquefaction by ground motions, than to the tsunami inundation after the tsunami run-up along the river. The latter damage of houses seems to be subjected to combination of forced vibration due to ground motions and direct tsunami wave pressure due to tsunami wave propagation.

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Building Damage Investigation of the 2010 Chile Earthquake and Tsunami Disaster

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A great earthquake of magnitude 8.8 struck on the Pacific coast of Chile, at 3:34a.m. local time on February 27, 2010, and the earthquake and Tsunami caused widespread damage in Chile. The group of Japanese and Peruvian researchers conducted disaster investigation especially for buildings from 26 April to 3 May, 2010.

Key Words : *Chile Earthquake, building damage, reinforced concrete, RC quake resisting wall*

1. INSTRUCTION

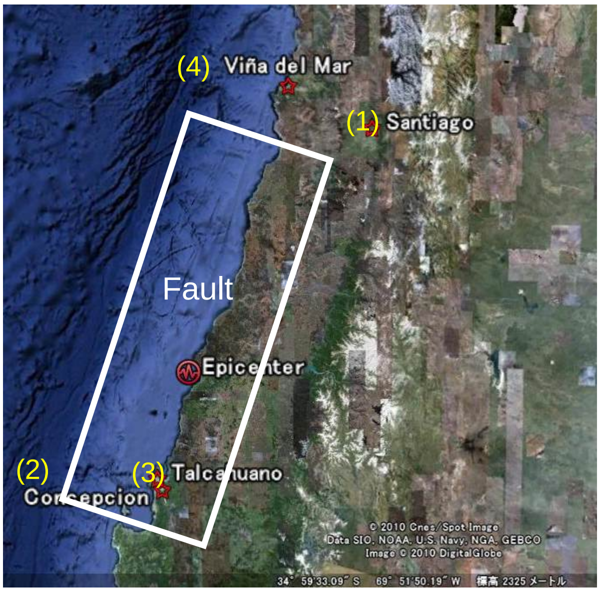
A great earthquake of Mw8.8 occurred at 3:34 A.M. on February 27, 2010 local time with the Pacific coast of Chile as the hypocenter. This earthquake collapsed or destroyed more than 810,000 buildings etc., resulting in more than 1.8 million victims including 432 deaths (as of March 27). When the earthquake occurred, in Peru, which a neighboring country of Chile, the Japan-Peru international joint research project, “Project for Enhancement of Earthquake and Tsunami Disaster Mitigation Technology in Peru” (JST-JICA Science and Technology Research Partnership for Sustainable Development Project, representative researcher: Fumio Yamazaki, professor at Chiba University, 2009-2014) was under way. Given that Peru and Chile are closely related to each other in terms of the seismotectonic and natural/social environments, and hence the findings obtained from the study on the great earthquake of Chile are expected to be mostly applied to Peru, with considerable ripple effects on other Latin-American countries, it was decided to perform investigation and information gathering on the damage caused by the earthquake and Tsunami that hit Chile, jointly with the counterpart from Peru. In addition, it was also decided that the second investigation team (team leader: Susumu

Kawano) would be dispatched from the Architectural Institute of Japan to the site around the same period to perform a joint investigation.

The investigation was performed from April 26 to May 3, approximately two months after the earthquake. Given the JICA Study Team (March 13 to 23) and a joint study team comprised of four societies (Japan Association for Earthquake Engineering, Japan Society of Civil Engineers, Japanese Geotechnical Society, and Architectural Institute of Japan) (March 27 to April 8) already dispatched from Japan and the limited investigation days, this investigation was devoted chiefly to performing on-the-spot inspection of disaster-stricken buildings, acquisition of design documents, hearing with relevant parties, and so on, with the objective of elaborately investigating reinforced concrete buildings. While our activities included the investigation of buildings equipped with a base isolation or seismic control structures, we would like to report in this paper our investigation results on the damage to reinforced concrete structures.

2. OUTLINE OF INVESTIGATION

The investigation was performed chiefly in principal cities (Santiago, Concepcion, and Viña del Mar) of Chile and the surroundings. Figure 1 was the investigation points and the locations of faults. Table 1 shows the list of the investigated buildings. The results of our detailed investigation on the underlined buildings of those listed in the table are as follows.



4/27	(1)	Santiago
4/28	(1)	Santiago
4/29	(2)	Concepcion
4/30	(2)	Concepcion, (3) Talcahuano
5/1	(4)	Viña Del Mar

Figure 1 Investigation points and locations of fault

Table 1 Investigated buildings

(Santiago)
B1. Torre Titanium (vibration control)
B2. Ciudad Empresarial
B3. Edificio Leones 1300
B4. Sol Oriente 1 and 2
B5. Edificio Don Luis
B6. Edificio Don Tristan
B7. Edificio Don Luis
B8. Hall Arnoldo Hax (Catolica Univ., seismic isolation)
B9. Comunidad Andalucia (seismic isolation)

(Concepcion)
B10. Torre O'Higgins 241
B11. LINCOYAN 440 (Torre Livertad)
B12. CAUPOLICAN 518
B13. Alto Rio
B14. SALAS 1343
B15. LOS CARRERAS 1535
B16. ROZAS 1145 (Edificio Don Feodra)
B17. FREIRE 1965 (Edificio Centro Mayor)
B18. Plaza Mayor
B19. BARROS ARANA 272

(Talcahuano)
B20.Edificio de Biblioteca Municipal de Talcahuano

(Viña del Mar)
B21. Building Festival
B22. ACHS (Asociacion Chilena de Seguridad) (seismic isolation)
B23. Efidicio Rio Petrohue

3. INVESTIGATION RESULTS OF BUILDING DAMAGE

(1) Damaged buildings in Santiago City

a) B4. Sol Oriente 1 and 2

It is an apartment complex constructed of box-frame-type reinforced concrete in 2007 with 18 stories above ground (2 stories underground) (Photo 1). The building was damaged particularly on the first basement level of the underground self parking lot (Photos 2, 3). The structural features and the summary of damage are follows:

- Multi-story shear wall structure connected by flat slabs.
- Flexural tension failure occurred in three structure planes out of five 4-span ones on the first basement. An end main reinforcement ruptured.
- The height of the north side multi-story shear wall on the basement is shorter by 1200 mm than on higher floors. In addition, only the northern end of the north side multi-story shear wall lacks an orthogonal wall (Figures 2, 3). Accordingly, the flexural strength of the north side multi-story shear wall is low on the first basement, likely resulting in the flexural tension failure in the south direction on the north side multi-story shear wall.

Photo 1
Appearance of the building

Photo 2
Underground parking lot

Photo 3
Shear wall on the first basement

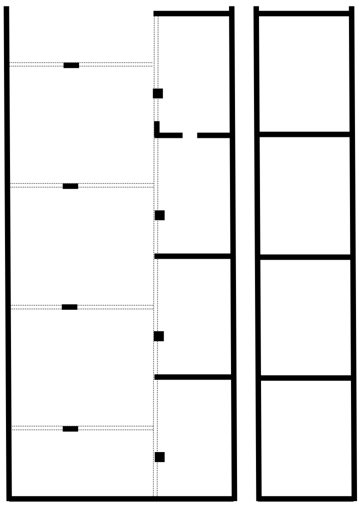


Figure 2 Basement plan view

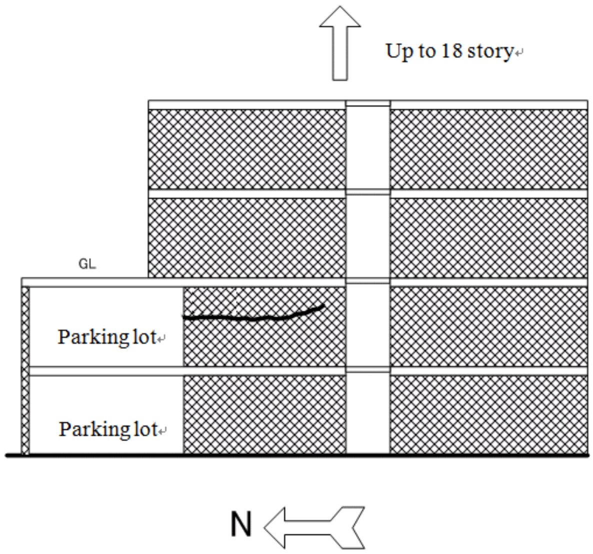


Figure 3 Building section view (sketch)

(2) Damaged buildings in Concepcion City

Concepcion City is a city located approximately 105 km away from the hypocenter with a population of approximately 220 thousand. The earthquake brought eight buildings into serious damage, of which one was completely collapsed. We could obtain entry permits to and design documents of several buildings thanks to the cooperation of the Urban Development Bureau and the Police Bureau of Concepcion City.

a) B11. LINCOYAN 440 (Torre Livertad)

It is an RC wall flat slab structure constructed in 1973. The building has 17 stories above ground and one basement (with no underground car park), of which the three lower floors are occupied by commercial tenants and the fourth and above floors are used for housing (Photo 4). The machine room on the first basement was hardly damaged. The non-structural brick wall collapsed more seriously on upper floors. The walls on the first and second floors failed in flexural tension with the wall-end main reinforcement fractured or buckled (Photo 5). While the building was damaged particularly on the walls in the northeast and southwest directions, little damage was observed on the walls in the orthogonal direction. The damage concentrated on the wall footing is likely attributable to the lack of flexural strength of the T section web resulting from the respective bending deformation of two multi-story shear walls arranged in parallel due to the limited floor slab area in the staircase (Figures 4, 5, 6).

Photo 4
Appearance of the building

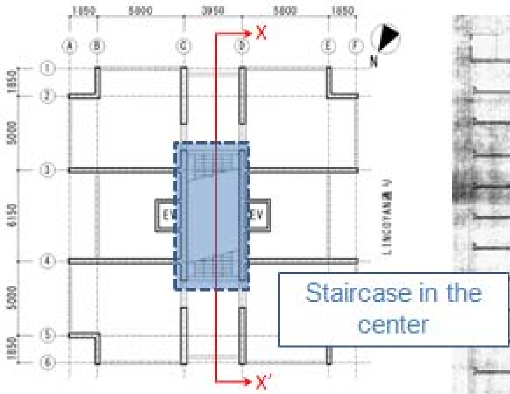


Figure 4
Building plan view

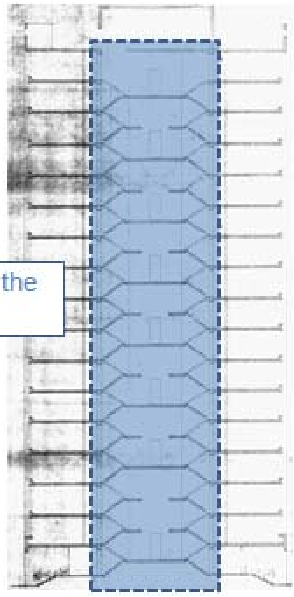


Figure 5
X-X' section view

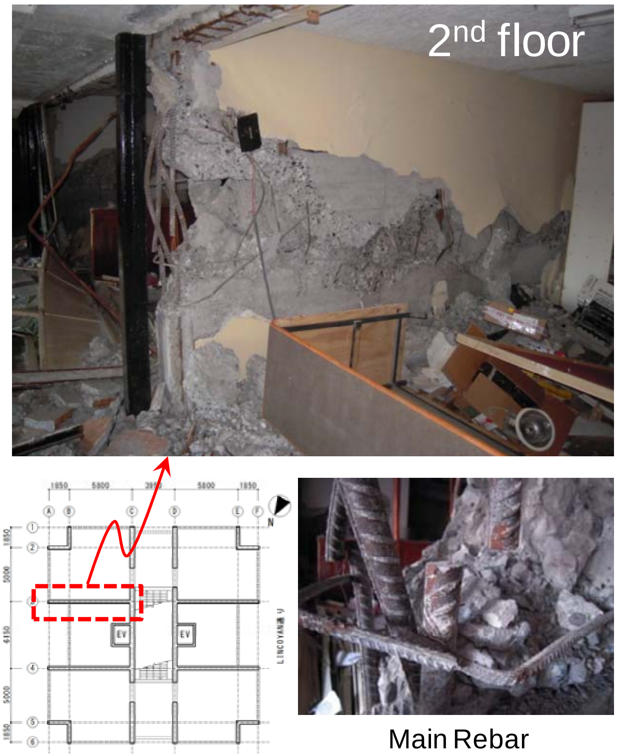


Photo 5
Wall fracture

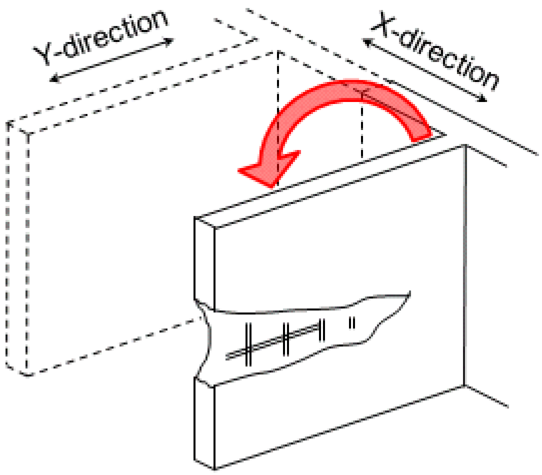


Figure 6
Failure mechanism of T-shaped section wall

b) B13. Alto Rio

It is a reinforced concrete apartment complex constructed in 2008 with 15 stories above ground and two stories underground (parking lot). The building completely fell down from the base on the first floor (Photo 6, 7). Photo 7 shows the appearance of all the reinforcing bars on the first floor having been pulled out or cut down from the wall pillars and load-bearing walls on the first floor during the overturning of the building. Conversely, little damage was observed on the underground end plane walls. As shown in the plan view of Figure 7, the walls on the first floor and the basements (parking lot) are smaller than those on the second and above floors in both length and volume. This fact may have resulted in the damage particularly on the wall footing on the basements.

Photo 6
Photo of the building before collapsed
(excerpted from the Web Page)

Photo 7
Collapsed building

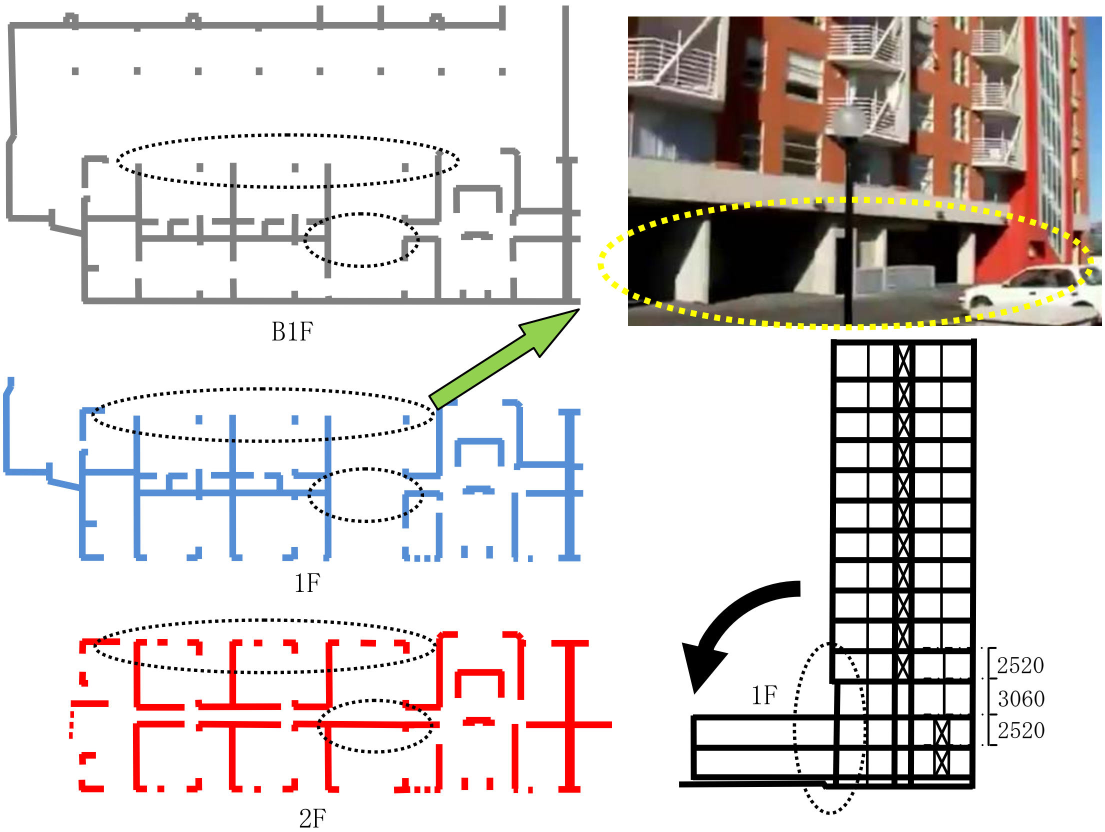


Figure 7 Difference in wall volume and layout among basement, first floor, and second floor

c) B14. SALAS 1343

It is an apartment complex constructed in 2007 with 13 stories above ground and an underground car park provided beside the building. It consists of two buildings arranged in L shape and connected with an expansion joint (Photo 8, Figure 8). It is constructed with a middle corridor in planar shape with more wall volume in the ridge direction. While the south side building was seriously damaged, the north side building was slightly damaged. The south side building seems to have suffered torsional vibration caused by stiffness eccentricity resulting from the many walls in the surrounding of elevators and staircases.

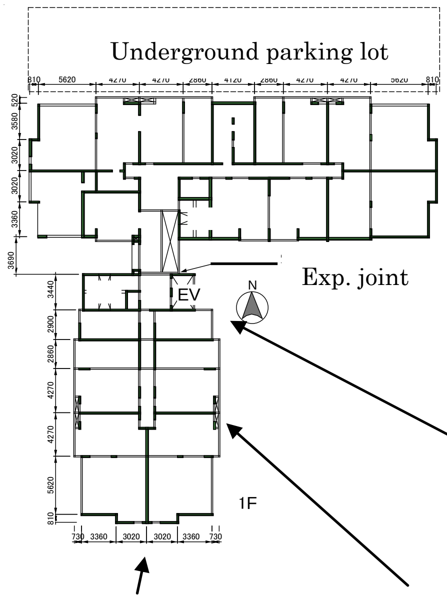


Photo 8
Appearance of the building

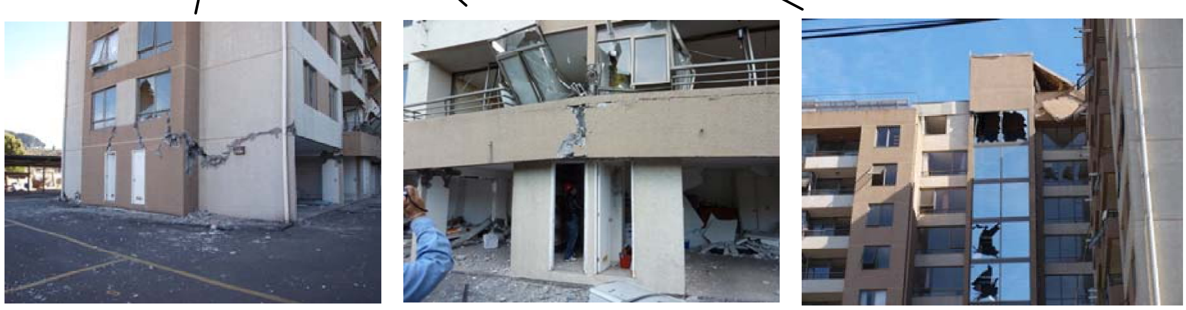


Figure 8 Plan view and damage

(3) Damaged buildings in Viña del Mar City

Viña del Mar City is a city with a population of approximately 300 thousand. The 1985 Chile Earthquake (magnitude 7.8, 150 deaths) damaged many high-rise RC buildings within the city.

a) B21. Building Festival

It is an apartment complex (wall-type flat slab structure) with 14 stories above ground and one basement. It was severely damaged (Photo 9). The building had undergone seismic retrofitting such as the placement of additional concrete for walls and beams and the additional installation of walls in response to the earthquake in 1985, but suffered damage in the recent earthquake such as flexural tension failure and separation of concrete-added walls in the wall footing (Photo 10, Figure 9).

Photo 9
Appearance of the building

Photo 10
Appearance of the building

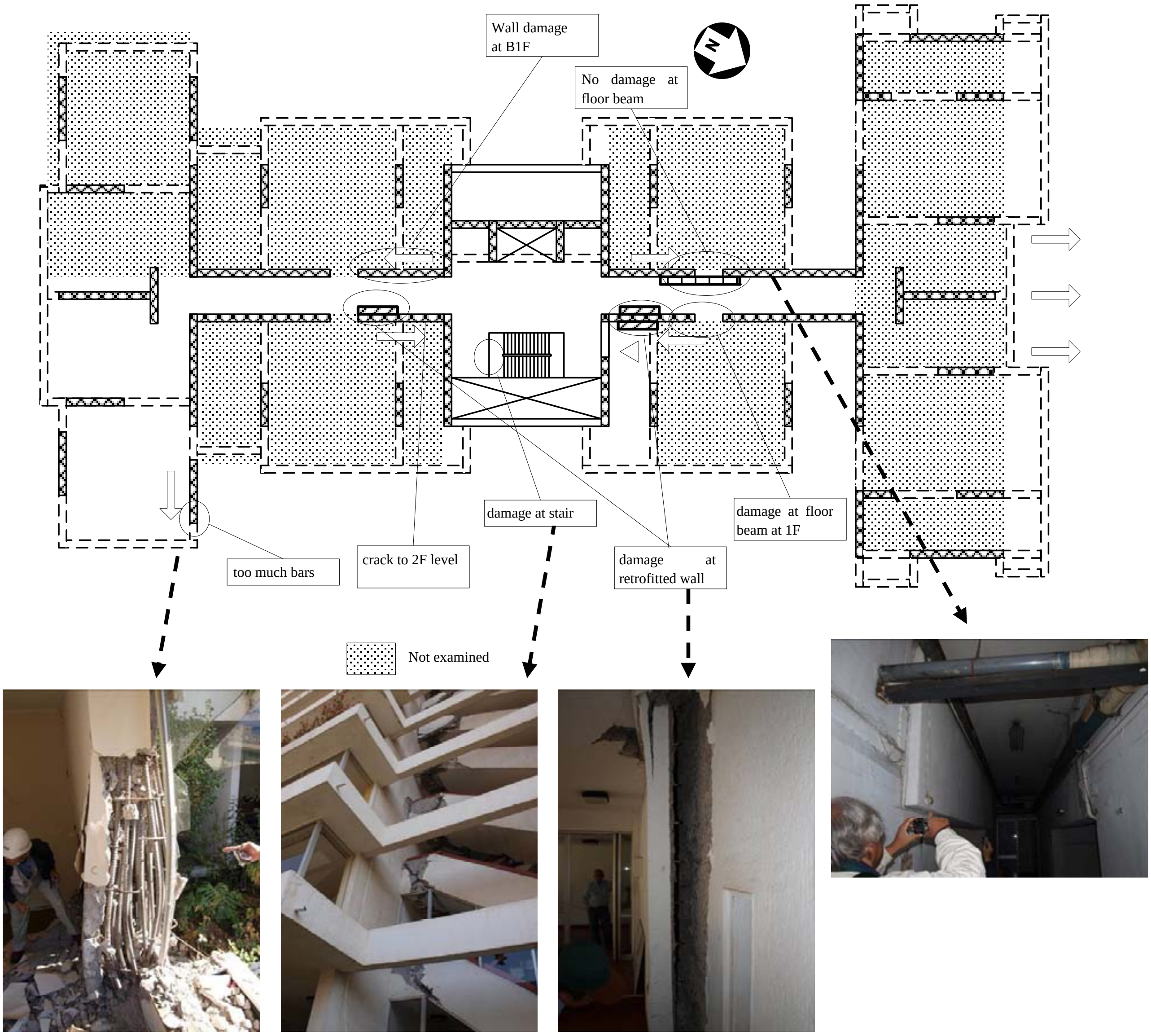


Figure 9 Plan view and damage

4. SUMMARY

The characteristics of the damaged buildings are as summarized below.

- Many of the damaged buildings are flat slab structures with no beam or frame column on the wall.
- The standard size of wall reinforcement is D10@250-D.
- At the wall end, confinement steel (or supplementary cross ties) is installed as well as bending reinforcement.
- The wall pillars, which are provided in place of pillars, are arranged longitudinally in the span direction for reasons of the layout of the parking lot. This fact may result in lower flexural strength and stiffness in the ridge direction.
- The length of a multi-story shear wall may be reduced in the underground parking lot space for the sake of vehicular traffic.
- A parking lot in the underground of the building may be constructed in a shape protruded in one direction. In this case, the parking lot is enclosed only by the three-side retaining walls immediately below the building, with the other side of wall set back in the ridge direction.
- Some walls or wall pillars in the span direction are not connected to orthogonal walls. Such walls include a wall extending in the span direction on the side without a retaining wall and a piloti-type wall pillar (ground parking lot). They were damaged probably due to the low flexural strength when the tensile load was exerted to the side with no orthogonal wall.
- The buildings have a relatively large number of stories and a high slenderness ratio. As a result, the walls of such buildings mostly underwent flexural tension failure. In addition, lack of enough strength to bear the story shear force on the compression side may result in collapse of the building.

Most of the severely damaged or collapsed buildings were high-rise constructions with 13 or more stories and damage concentrated on the footing of the multi-story shear wall observed as a common characteristic. Conversely, most buildings in cities appeared to be sound and few buildings suffered intermediate damage, e.g. slight or medium damage. This may be a characteristic of damage to box frame constructions without plastic deformability. The damage can be considered generally minor, in view of the great magnitude of the recent earthquake at 8.8. While elaborate analysis is still required as to the extent of the seismic force applied to the buildings, given the fact that the damage remained so modest after the great earthquake, the Chilean Seismic Code seems to have functioned extremely well. One of the factors behind the major lack of damage to buildings in the recent earthquake was the positive introduction of the load-bearing wall.

The Chilean Seismic Code includes a provision likely encouraging the positive introduction of the load-bearing wall such as a strict restriction of deformation and reduction of the design seismic force according to the load ratio of the load-bearing wall. In Japan, the height of wall-type rigid-frame structures is limited to 15 stories. Given the modest damage to buildings in the recent Chile Earthquake and the continuous usability of post-earthquake buildings, Japan may also need to recognize anew the benefits of box frame constructions.
From the research perspective, a design method needs to be established to prevent such brittle failure after flexural yielding as observed in the recent seismic damage. Structural testing on flexural failure of load-bearing walls is not common in Japan and future research and development is awaited.

ACKNOWLEDGMENT

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Development of Spatial Information Database of Building Damage and Tsunami Inundation Areas following the 2010 Chile Earthquake

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This paper presents the results of a field survey conducted by the authors after the 2010 Chile earthquake. The authors visited the affected area about a month after the earthquake. The GIS datasets for the damage levels of buildings in Talca and the tsunami-inundated areas in Talcahuano, Dichato, and Constitución are constructed in this study, and a series of fundamental analyses are performed using a digital elevation model (DEM). Further, the usefulness of satellite images captured after the earthquake to detect damaged buildings in Talca is discussed using the GIS datasets constructed in this study.

Key Words : *2010 Chile earthquake, GIS, building damage, tsunami-inundated area, digital elevation model (DEM)*

1. INTRODUCTION

The 2010 Chile earthquake occurred off the coast of the Maule Region of Chile on February 27, 2010, at 03:34 local time (06:34 UTC) with a magnitude of 8.8 on the moment magnitude scale. The epicenter was offshore from the Maule Region, approximately 335 km southwest of Santiago, the capital of Chile, and 105 km north-northeast of Chile's second largest city, Concepción. It is reported that a severe ground motion with the Modified Mercalli Intensity (MMI) scale of VII was felt widely in Chile and that the extensive damage was caused by the ground shaking and tsunami[1)]. The total economic loss estimates range from USD 15 to 30 billion, which correspond to 10% to 15% of Chile's real GDP[2)]. According to the report on the scene, the actual death toll was 486 as of March 8, 2010, and approximately 370,000 homes were damaged[2)].

The authors visited the affected area about a month after the event as part of an international research project "Enhancement of earthquake and tsunami disaster mitigation technology in Peru"[3)], which is under the research program "Science and Technology Research Partnership for Sustainable Development (SATREPS)"[4)] supported by the Japan Science and Technology Agency (JST) and the Japan International Cooperation Agency (JICA). The lessons learned from the 2010 Chile earthquake are expected to apply to the earthquake disaster mitigation technologies in Peru because the two countries have common regional tectonics and social surroundings.

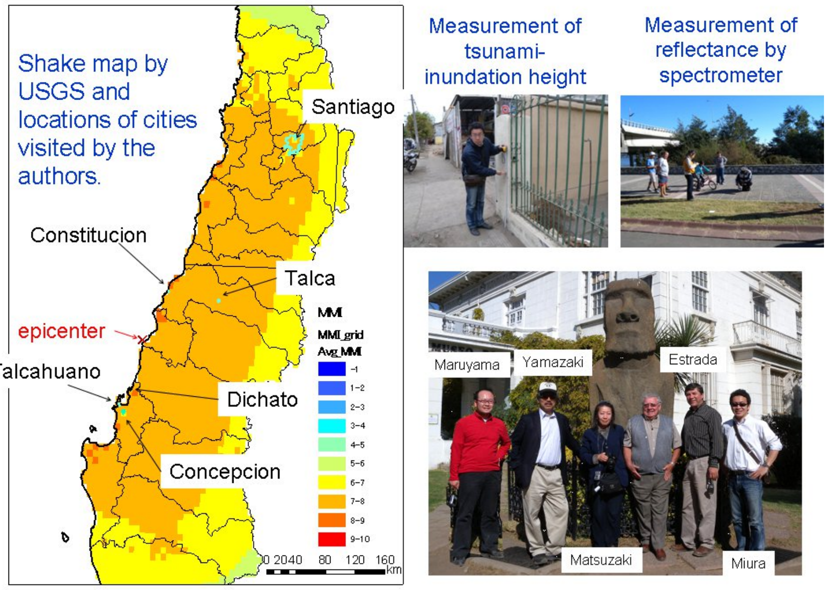

Fig. 1 Locations of cities visited by the authors and outline of field survey by the authors.

Fig. 2 Survey route and field photos in Santiago—April 2, 2010

Three teams of Japanese and Peruvian researchers were dispatched by the SATREPS project to carry out field surveys. In this paper, the results of the field survey performed by Damage Assessment Group and Disaster Mitigation Plan Group are presented. The spatial damage data, topographical maps, and satellite images provided by different institutions are compiled by the geographical information system (GIS), and the primitive analyses are conducted to reveal the characteristics of the tsunami-inundated areas in view of elevations and damage incidents to adobe and unreinforced masonry buildings, which are also widely seen in Peru.

2. OUTLINE OF FIELD SURVEY

The authors arrived in Santiago on April 2, 2010. We drove to Concepcíon the next day and visited the tsunami-affected areas of Talcahuano, Dichato, and Constitución. We moved to Talca on April 7 and left Santiago on April 8. Before leaving, we visited Valparaíso and Viña del Mar. **Figure 1** shows the locations of the cities that we visited during the survey.

Figure 2 shows the route of our field survey in Santiago and some field photographs. The route was recorded by a portable GPS device during the survey and the location of the photo shooting could be identified as the location data were embedded in the Exchangeable Image File Format (EXIF). An RC building with 20 stories constructed in 2003 suffered from shear failures in columns and walls at the first and the second stories. A collapsed highway bridge and an RC building with the collapsed first floor were found. The locations of these sites are also shown in the survey route in **Fig. 2**.

Fig. 3 Survey route and field photos in Concepcíon—April 4, 2010

Fig. 4 Survey route and field photos in Dichato—April 5, 2010

Figure 3 shows the survey route in Concepcíon. An RC building with the damaged middle floor was found at the site numbered 1. An RC building with 15 stories had collapsed completely at the site numbered 2. The road bridges collapsed at sites 3 and 4. The temporary bridge girder was constructed two days after the earthquake at site 3. Although the photos are not shown in this paper, the adobe and unreinforced masonry constructions were severely damaged in the urban area.

Figure 4 shows the survey route in Dichato. It is reported that more than 80% of the built-up area in Dichato suffered from tsunami[5)]. As shown in the field photos, the buildings collapsed because of the tsunami waves. A ship was conveyed against the river flow because of the tsunami and eventually found at site 3.

3. CONSTRUCTION OF GIS FOR BUILDING DAMAGE AND TSUNAMI-INUNDATED AREA

(1) Building damage GIS in Talca

Talca is the capital of both Talca Province and Maule Region. Its population is approximately 200,000, and it is approximately 250 km south of Santiago and 60 km northwest of the epicenter of the 2010 Chile Earthquake[5)]. According to USGS[1)], Talca was affected with a severe ground motion with the MMI scale of VII.

During our survey, we interviewed officials from Maule Regional Office to investigate the damage of buildings. As a result of our interview, an image file that shows the damage levels of buildings was provided. The polygons, which indicate the building lots, are classified into four levels, namely, to be removed, to be repaired, no damage, and under investigation. It should be noted that the image file was compiled with the damage dataset as of March 31, 2010.

In this study, the location of the image file was established in terms of map projections. The satellite image and road data presented in Google Earth were employed as a base map to georeference the image file. Then, the

Fig. 5 GIS file to show the damage levels of buildings in Talca and locations of field photos

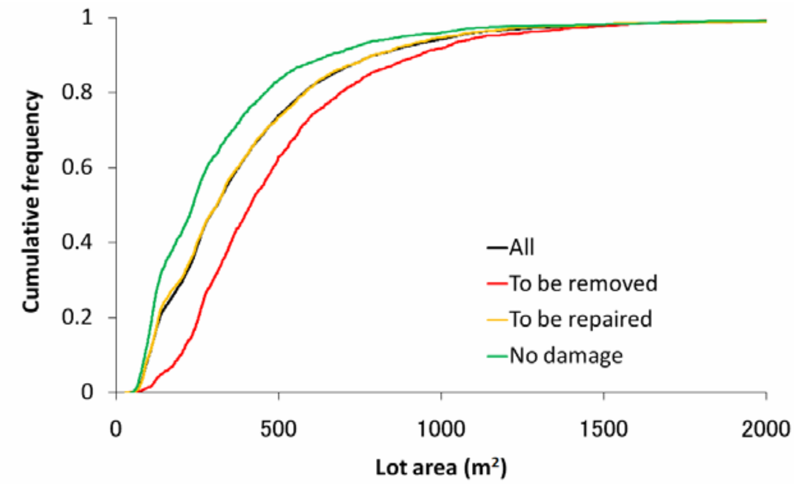

Fig. 6 Cumulative frequencies of the areas of building lots with respect to the damage level

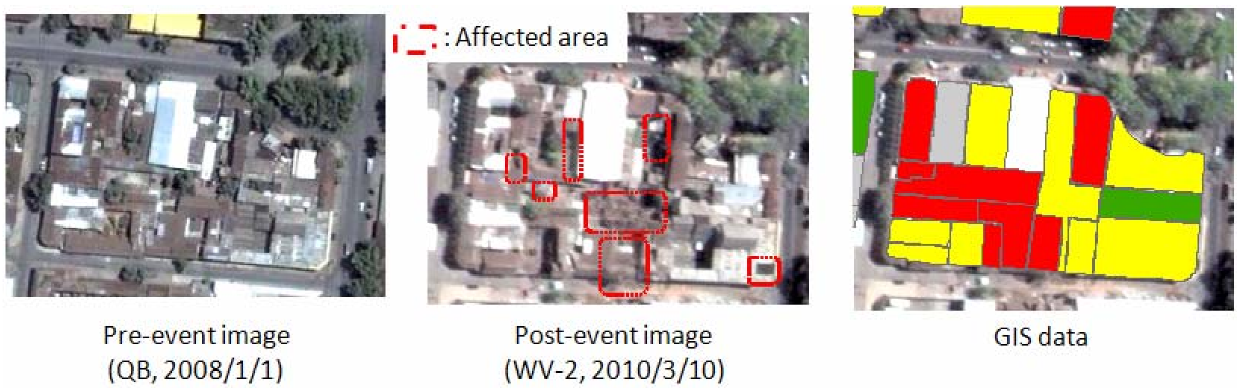

Fig. 7 Comparison between pre- and post-event satellite images to detect affected buildings

image file was converted to a GIS file with polygons to identify the damage levels of buildings. **Figure 5** shows the developed GIS file presented by Google Earth and some field photos to show the examples of damaged buildings.

In all, 5617 polygons were projected to the map coordinate system. 1559 (27.8%), 1872 (33.3%), and 1864 (33.2%) buildings were classified as to be removed, to be repaired, and no damage, respectively. The typical construction types in Talca are adobe and unreinforced masonry buildings, which are primarily used for older constructions with 2–4 stories (dating back to before the 1960s–70s). Modern buildings that were designed according to the current codes suffered minor, repairable damage, while a large number of adobe and unreinforced masonry constructions suffered significant damage[6].

Figure 6 shows the cumulative frequencies of the areas of building lots with respect to the damage level.

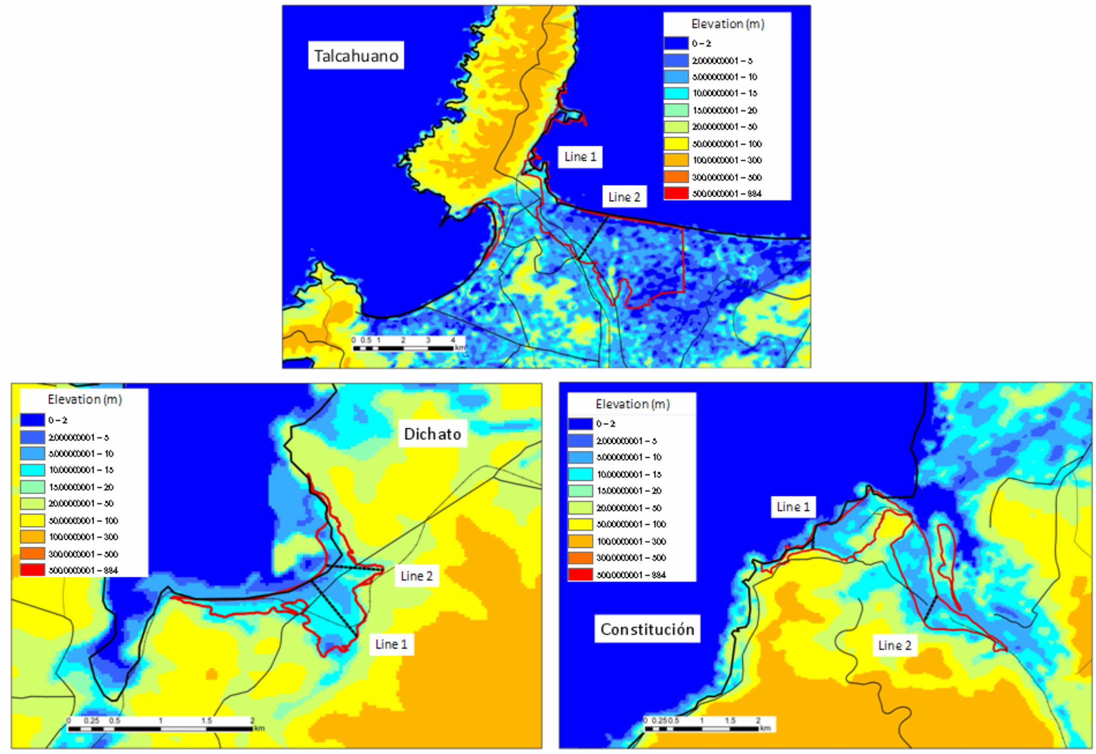

Fig. 8 Tsunami-inundated areas in Talcahuano, Dichato, and Constitución

The mean of all the georeferenced areas was approximately 430 m^2 and was almost equal to that of the areas associated with the buildings to be repaired. The mean of the lot areas of the buildings to be non-damaged was approximately 340 m^2, which was considerably smaller than that of the buildings to be removed. On the basis of the results, it has been speculated that the newer buildings are constructed in relatively small lots; however, the construction periods are not available at this moment.

Recent advancements in remote sensing technologies and their applications have made it possible to use remotely sensed imagery for estimating the damage distribution due to natural disasters. Among them, high-resolution optical satellite imagery, which has become available in the last decade, has made satellite remote sensing more useful in disaster management since even the damage status of individual buildings can be identified[7), 8)]. **Figure 7** compares the pre- and post-event high-resolution optical satellite images with the GIS dataset shown in **Fig. 5**. As for the pre- and post-event images, the image captured by QuickBird[9)] on January 1, 2008, which is presented in Google Earth, and that captured by WorldView-2[10)] on March 10, 2010, are employed in this study. A comparison of the pre- and post-event images revealed that some of the affected buildings could be visually detected, but not all the damaged ones could be identified appropriately. Since the post-event image was captured with the large off-Nadia angle (40.3°), the quality of image is not sufficient for visual damage inspection. Moreover, the number of affected buildings whose roofs had completely collapsed is small in Talca. Hence, it can be concluded that the damaged buildings in Talca are difficult to be detected through visual damage inspection using satellite images.

(2) Development of GIS for tsunami-inundated area

Various institutions released the maps to show the damage distribution at their Web sites after the 2010 Chile earthquake. The tsunami-inundated areas interpreted from satellite and aerial images were published by National Office of Emergency of the Interior Ministry (ONEMI) of Chile[11)]. On the basis of the maps, the number of affected buildings and that of causalities were estimated.

In this study, the tsunami-inundated areas were projected onto a map coordinate system, and the topographical conditions were evaluated in terms of the elevation. The inundated areas in Talcahuano, Dichato, and Constitución were converted to the GIS data and compared with the digital elevation model (DEM). The DEM employed in this study is the ASTER Global Digital Elevation Model (GDEM) developed by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA)[12)]. The ASTER GDEM is a highly accurate DEM covering all the land on earth with the

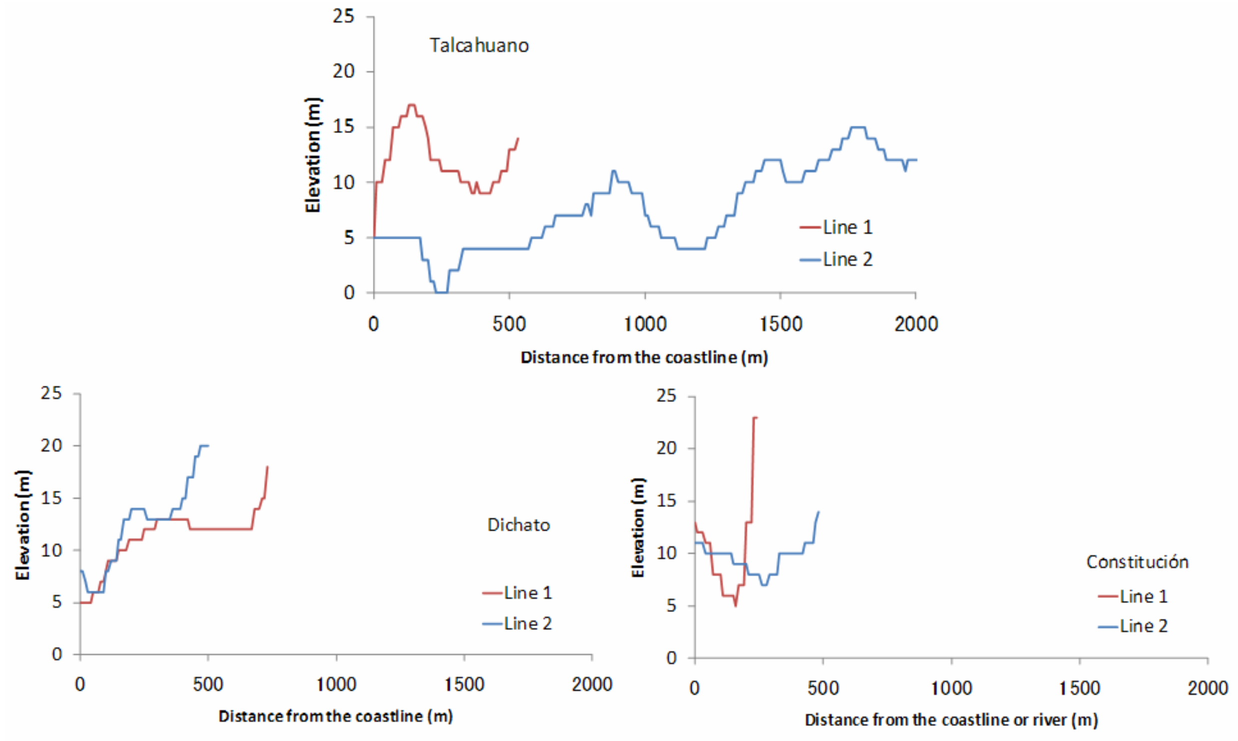

Fig. 9 Elevations along the transverse lines set in Fig. 8

Fig. 10 Measurement of tsunami inundation depth in Talcahuano

spatial resolution of 30 m.

Figure 8 shows the tsunami-inundated areas in Talcahuano, Dichato, and Constitución and the distributions of the elevation derived from the ASTER GDEM. The elevations in the inundated areas are lower than 20 m on the whole except for a certain area in Constitución. As shown in the figure, we set the two traverse lines in each inundated area. The elevations were extracted along the two lines. The extracted elevations are illustrated in terms of the distance from the coastline in **Fig. 9**. As for Line 2 in Constitución, the elevations are presented with respect to the distance from the Maule River. The relatively low elevations and slow grades result in long travel distances of the tsunami wave. According to Line 2 in Talcahuano, the tsunami wave could travel approximately 2000 m from the coastline. Line 1 in Constitución was assigned to identify the surveyed site by Imamura et al.[13]. According to their report, the tsunami runup height was 28.3 m at the site. Since the DEM used in this study is a global dataset that consists of 30-m grid cells, the elevation at the site is estimated to be approximately 23 m. The slope is estimated to be approximately 67% and is almost equivalent to that reported by Imamura et al., which is 63.5%[13].

As shown in **Fig. 10**, the inundation depth was measured at several sites in the three cities. The inundation depth along the beachfront street in Talcahuano was larger than 150 cm, but a depth of 55 cm was observed in its bystreet (site 4). **Figure 11** summarizes the measurements in the three cities. The inundation depth is presented with respect to the elevation and the distance from the coastline. As for the results in Constitución, the records are shown with respect to the distance from the Maule River. A clear tendency is not seen in the rela-

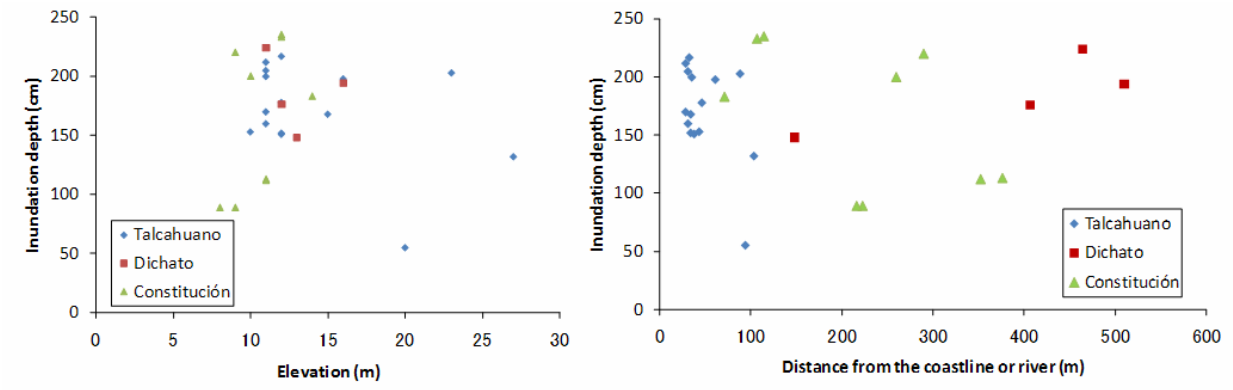

Fig. 11 Summary of the measurement of tsunami inundation depth

tionship between the tsunami inundation depth and the elevation. The recorded depth in Talcahuano and Constitución decreased with an increase in the distance from the coastline or the river; however, this tendency is not seen from the records in Dichato because of the insufficient number of measurements.

4. CONCLUSIONS

In this paper, the results of a field survey conducted after the 2010 Chile earthquake by the authors during April 2–8, 2010, are presented. The GIS dataset for the building damage in Talca was developed by establishing the location of the image file in terms of map projections. The usefulness of high-resolution satellite images to detect the building damage in Talca was investigated with the aid of the constructed GIS dataset. Moreover, the tsunami inundation maps published by ONEMI were georeferenced, and the characteristics of the inundated areas were evaluated in view of the elevation.

According to the relationship between the building damage levels and the lot areas, the mean of the areas associated with the non-damaged buildings was the smallest, while the mean of the areas associated with the buildings to be removed was the largest. In Talca, modern buildings that were designed according to the current codes suffered minor, repairable damage, while a large number of adobe and unreinforced masonry constructions, which were built in the 1960s–70s, suffered significant damage. On the basis of these circumstances, it has been speculated that the newer buildings may be constructed in relatively small lots; however, the construction periods are not available at this moment. According to the results of a visual damage inspection using pre- and post-event satellite images, it was concluded that the damaged buildings in Talca could not be appropriately detected because of their damage patterns and the quality of the post-event satellite image.

A comparison of the georeferenced tsunami-inundated areas with the elevations obtained from the ASTER GDEM revealed that the elevations in the inundated areas were lower than 20 m on the whole except for a certain area. A clear tendency was not seen in the relationship between the tsunami inundation depth and the elevation. The recorded inundation depth in Talcahuano and Constitución decreased with an increase in the distance from the coastline or the river.

These findings of our field survey after the 2010 Chile earthquake will be expanded in the earthquake and tsunami disaster mitigation technology in Peru through the SATREPS project.

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