

FIELD SURVEY OF THE 2010 TSUNAMI IN CHILE

**Shunichi Koshimura¹⁾, Masashi Matsuoka²⁾, Masafumi Matsuyama³⁾,
Takumi Yoshii⁴⁾, Erick Mas⁵⁾, Cesar Jimenez⁶⁾ and Fumio Yamazaki⁷⁾**

1) Associate Professor, Disaster Control Research Center, Graduate School of Engineering, Tohoku University, Japan

2) Senior Research Scientist, Geoinformation Center, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Japan

3) Senior Researcher, Civil Engineering Research Laboratory, Central Research Institute of Electric Power Industry, Japan

4) Research Scientist, Environmental Science Research Laboratory, Central Research Institute of Electric Power Industry, Japan

5) Graduate Student, Graduate School of Engineering, Tohoku University, Japan

6) Research Scientist, Direccion de Hidrografia y Navegacion, Peru

*7) Professor, Department of Urban Environment Systems, Graduate School of Engineering, Chiba University, Japan
koshimura@tsunami2.civil.tohoku.ac.jp, m.matsuoka@aist.go.jp, matsu@criepi.denken.or.jp, takumi@criepi.denken.or.jp,
erick@tsunami2.civil.tohoku.ac.jp, cesarsud86@hotmail.com, fumio.yamazaki@faculty.chiba-u.jp*

Abstract: 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.

1. INTRODUCTION

On 27 February 2010, a megathrust earthquake of M8.8 (Figure.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.

2. POST TSUNAMI FIELD SURVEY

2.1 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. Figure.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.

2.2 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. Figures. 3 and 4 show the longshore distribution of the measured tsunami heights and depths. 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.

3. RESULTS

3.1 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.

Figure. 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 (Figures. 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 (Figure. 5(a)).

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 (Figure. 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.

3.2 Inspection of satellite images

Inspecting pre and post event satellite images and ground photos helps to understand multi aspects of tsunami disaster. Figure. 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 Talcahuano 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 (Figure. 8) that the coastal

sand were eroded by inland penetration of tsunami.

3.3 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.

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

Here, we focused on the eastern bank of the canal in Talcahuano. Figure. 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 (Figures. 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 (Figure. 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. Figure. 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.

3.4 Tumbes, Puerto Ingles and Llico

Tumbes locates and Puerto Ingles are the coastal communities, which were isolated by the limited road access. Figure.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 (Figure.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.

3.5 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. Figure. 14 represents the measured tsunami run-up height and flow depths. The tsunami penetrated approximately 800 m inland to 10 m altitude. Figures. 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.

4. 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.

Acknowledgements:

This research was sponsored in part by Japan Science and Technology Agency (JST) through the project of Science and Technology Research Partnership for Sustainable Development (SATREPS).

References:

- Ruegg, J.C., A. Rudloff, C. Vigny, R. Madariaga, J.B. de Chabaliér, J. Campos, E. Kausel, S. Barrientos, D. Dimitrov, Interseismic strain accumulation measured by GPS in the seismic gap between Constitución and Concepción in Chile, *Physics of the Earth and Planetary Interiors*, 175, pp.78-85, 2009.
- U.S. Geological Survey,
<<http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010t fan/>>
- West Coast/Alaska Tsunami Warning Center, NOAA,
<http://wcatwc.arh.noaa.gov/previous.events/Chile_02-27-10/Tsunami-02-27-10.htm>

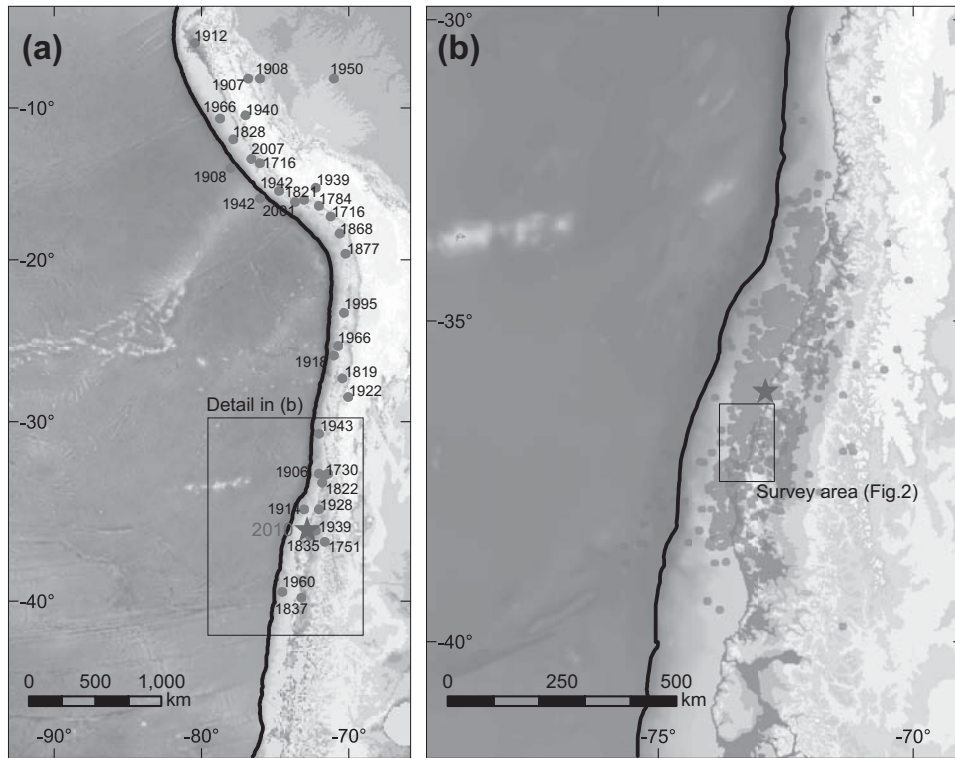


Figure1 (a) Significant earthquakes of more than M8 since 1700 and the epicenter of the 27 February 2010 Chile earthquake. (b) Mainshock (red star) and aftershocks of the 2010 Chilean earthquake (gray dots) during one day since the mainshock occurred.

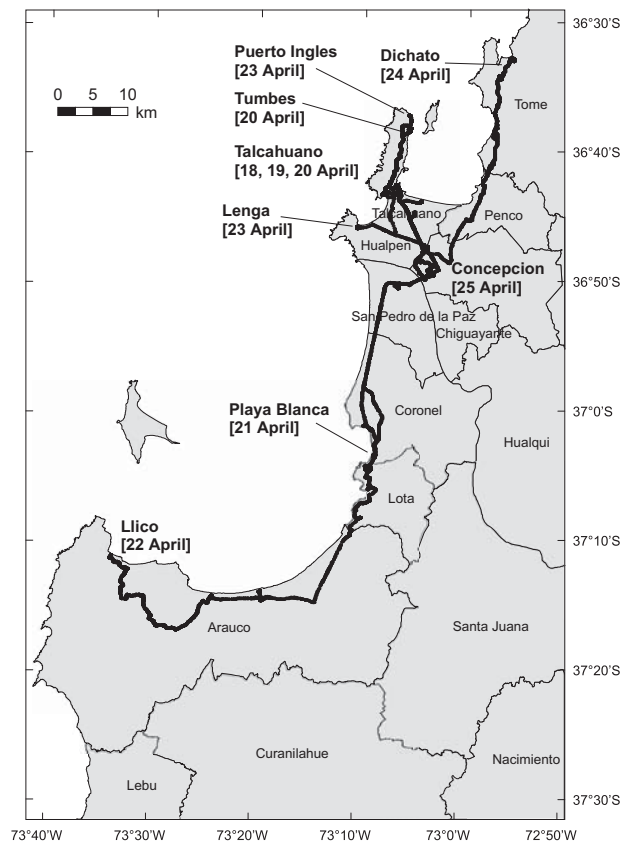


Figure 2 The route and area of the post-tsunami field survey in Biobio region.

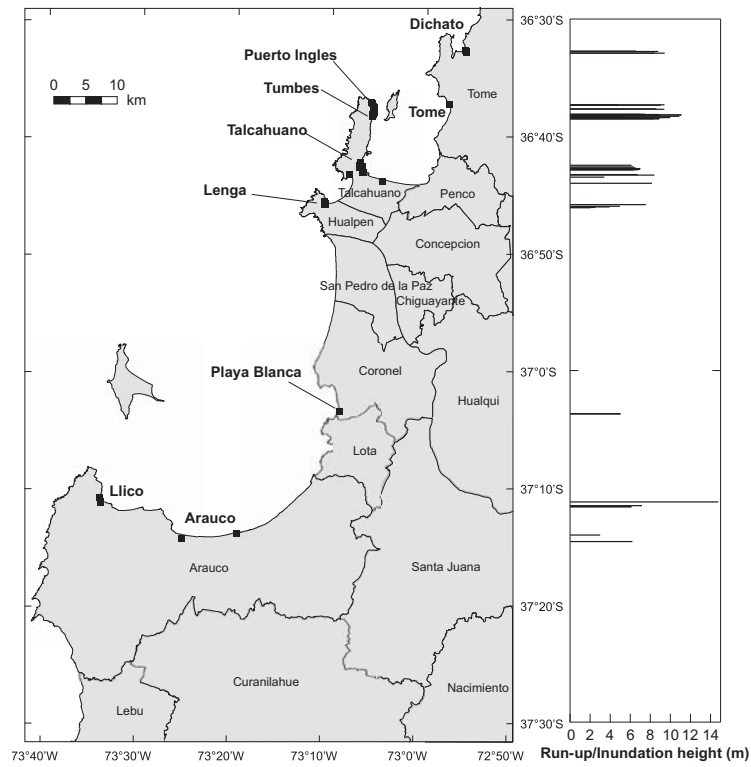


Figure3 Longshore distribution of inundation and run-up height above the astronomical tide level when the tsunami arrived. Tide correction was made by using tide table in Talcahuano.

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

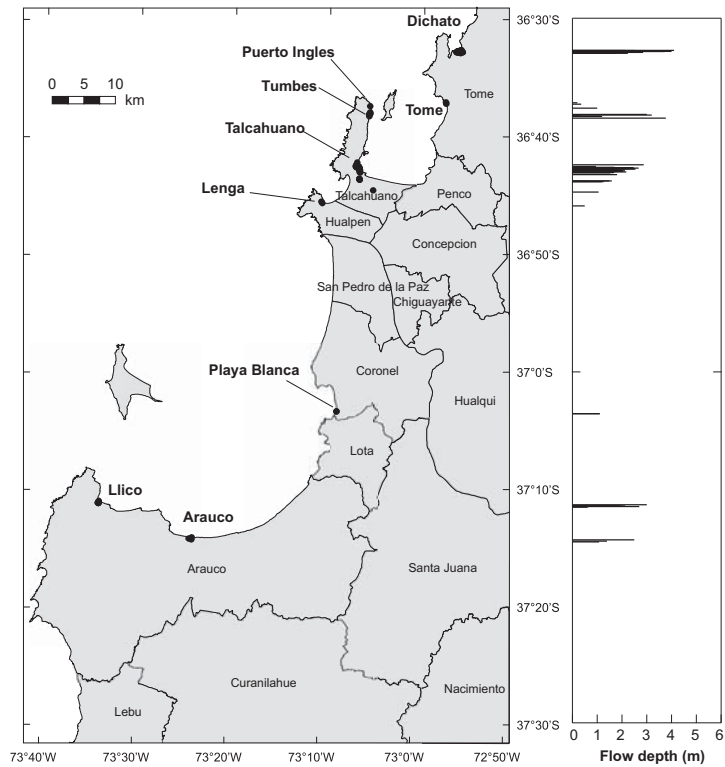


Figure 4 Longshore distribution of measured flow depths, which were measured as a height of watermark of tsunami penetration above the ground level.

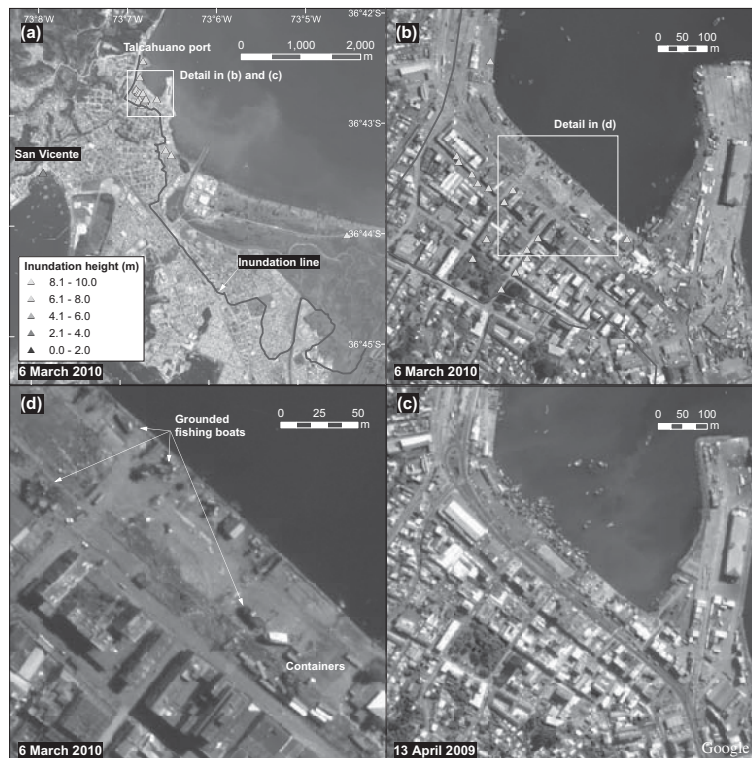


Figure 5 (a) Result of tsunami height measurement in Talcahuano. The red line indicates the extent of inundation zone which was obtained by the interview with CATOE (Centro de Alertamiento Temprano y Oficina de Emergencia). (b) Damage in Talcahuano found in the post-event satellite image (WorldView-2). (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.

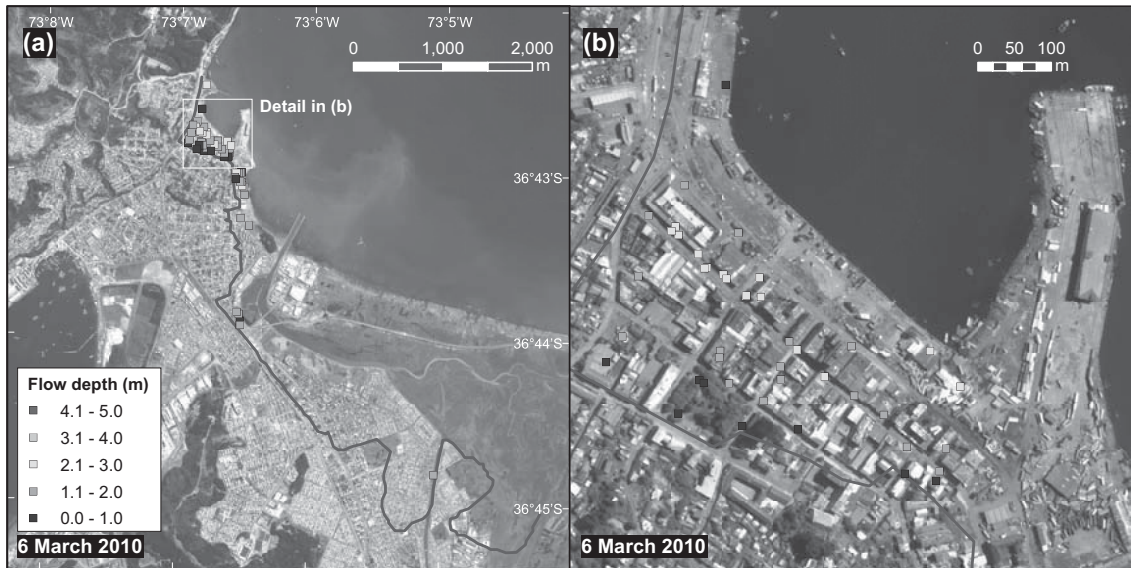


Figure 6 Result of tsunami flow depth measurement in the town of Talcahuano. The tsunami penetrated approximately 100 m inland with the flow depth of up to 2-3 m.

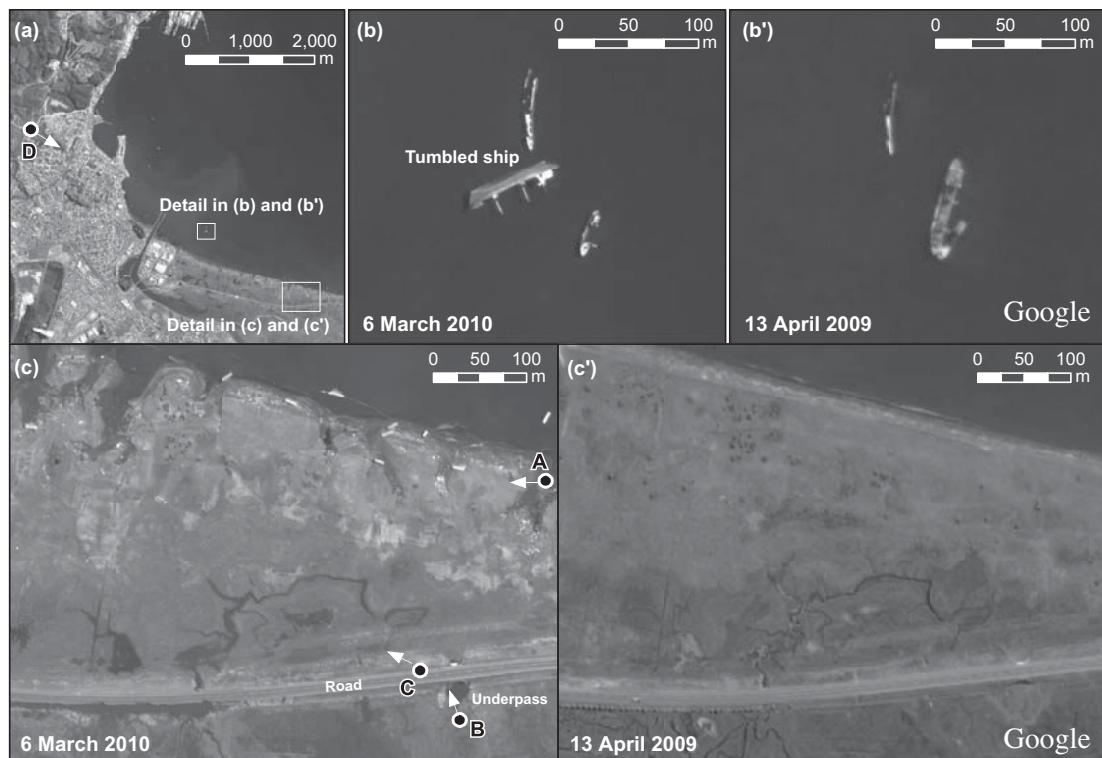


Figure 7 Pre and post event satellite images in Talcahuano. Points A to D represent the position of ground photos taken by the authors (Figure 8). White arrow is approximate direction of the camera focus. (a) Overview of Talcahuano port. (b) and (b') A 70m-long tumbled ship found the east of waterway.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



Figure 8 Ground photos in Talcahuano taken by the authors. Each point is identified in Figure 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.

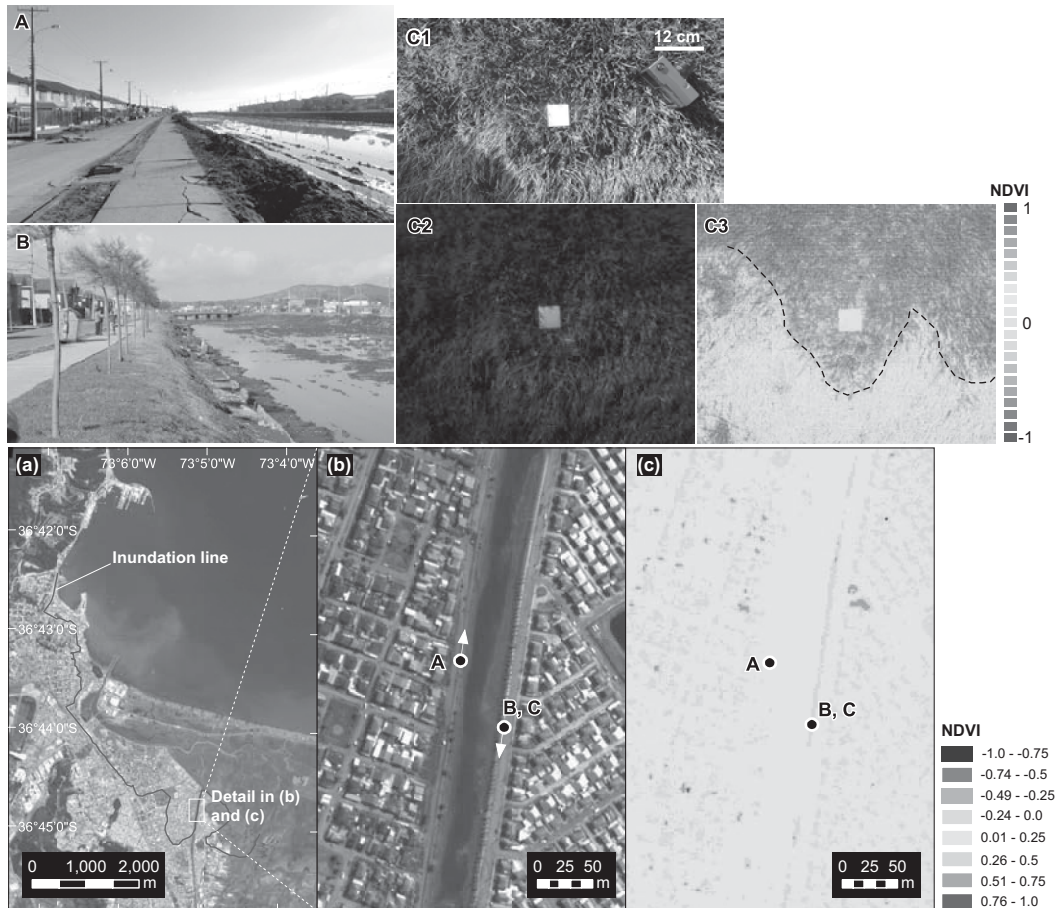


Figure 9 (a) Inspection area of saltwater penetration, (b) Pan-sharpened multi-spectral image of WorldView-2 acquired on 6 March 2010. A, B and C is the point of ground photos, White arrow is approximate direction of camera focus. (c) Spatial distribution of NDVI Western. A and B : Ground photos taken 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.

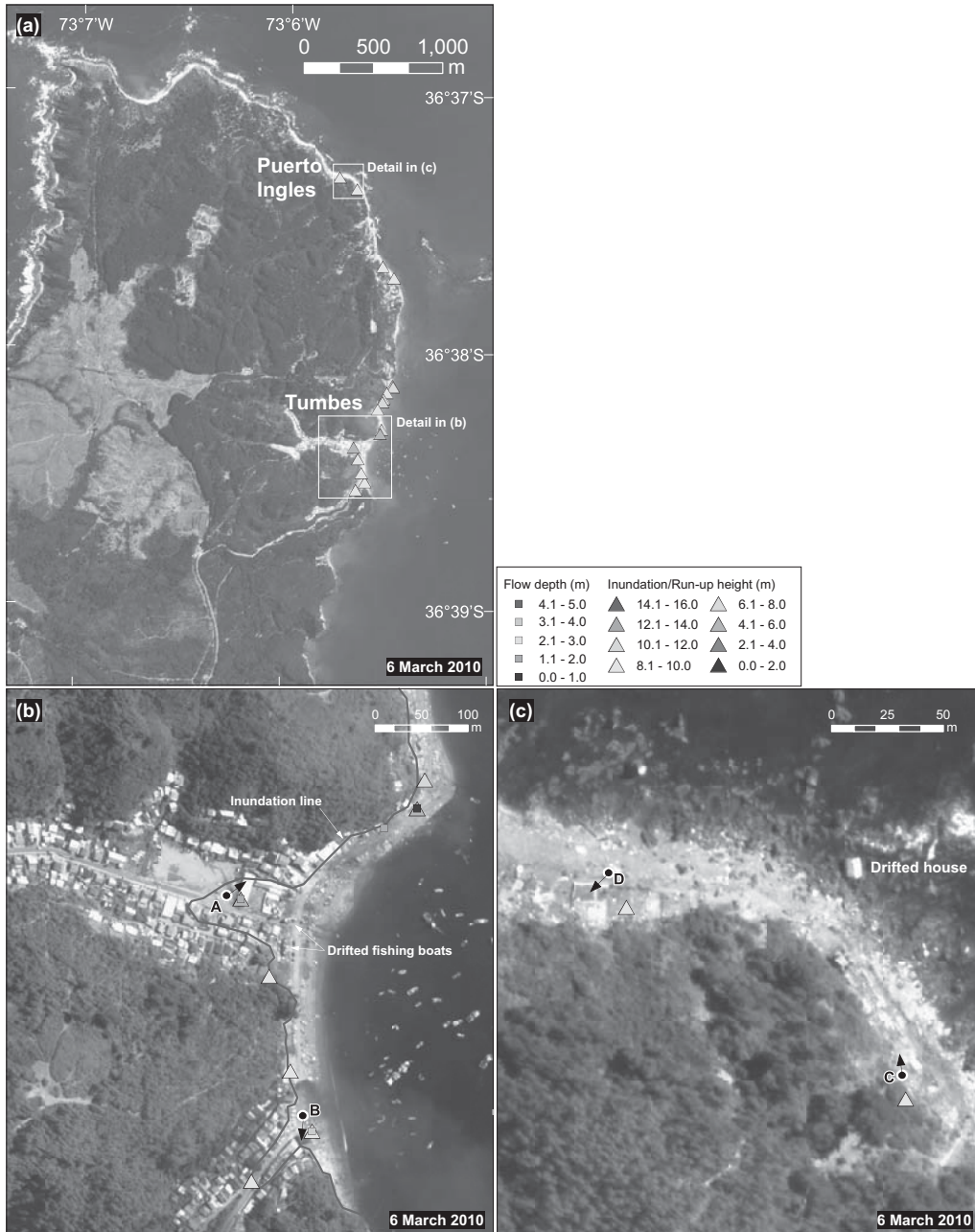


Figure 10 (a) Overview of tsunami measurements (inundation and run-up heights) in Tumbes and Puerto Ingles. (b) Detailed features of the measurements and the damage in Tumbes. (c) Devastated damage in Puerto Ingles. Point A to D is the position of ground photos in Figure 11 respectively with the arrow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

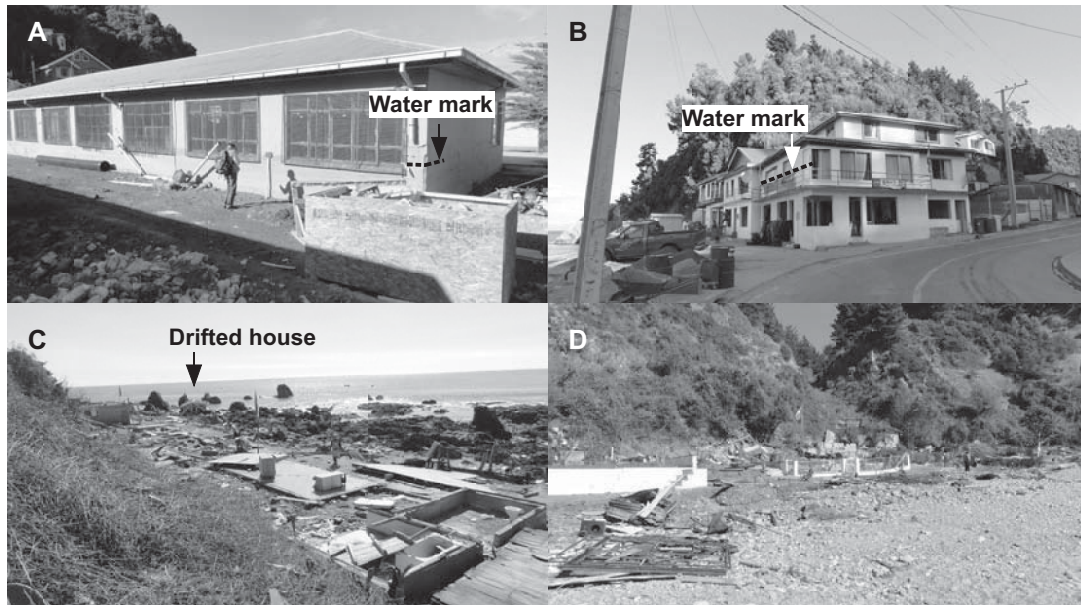


Figure 11 Ground photos from Tumbes (A, B) and from Puerto Ingles (C, D). A : Watermark on school building. B : Watermark on the house of Tumbes, C and D : Completely devastated village of Puerto Ingles.



Figure 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 Figure 13.

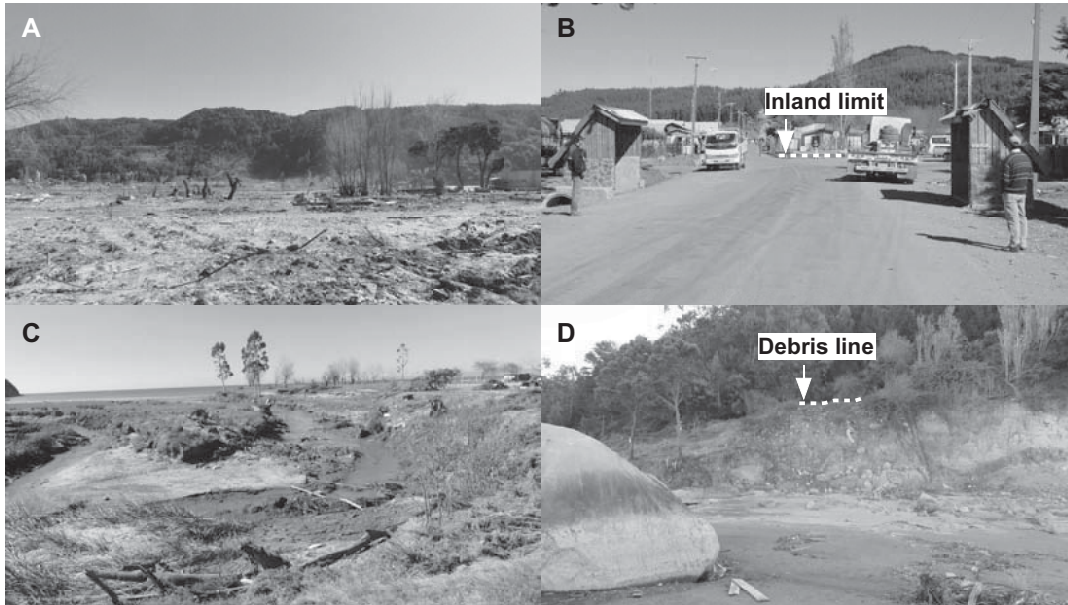


Figure 13 Ground photos from Llico. A : Completely devastated village. In the village, there were around 60 houses before tsunami. Almost all the houses were washed-away. B : Inland limit of tsunami inundation that is approximately 400 m from the shoreline. C : Tsunami run-up along the river. D : Tsunami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



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



Figure 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 (Figure 16). White arrow is approximate direction of the camera focus.

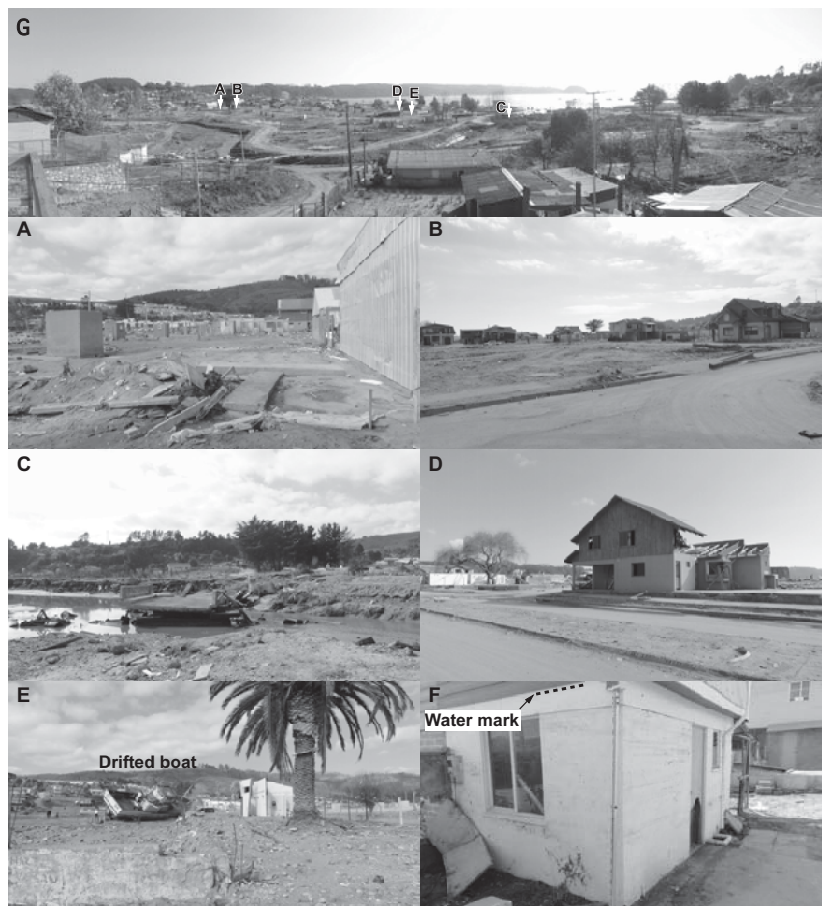


Figure 16 Ground photos from Dichato. A and B : Most devastated area. Only the unit of bathroom is remained. C : Damage on a bridge and erosion by tsunami inundation. D: Withstanding house, but significant damage. E : Drifted boat. F : Watermark on the house (approximately 2 m of flow depth). G : Panoramic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