THE M_W8.8 MAULE CHILE EARTHQUAKE OF 27^{TH} FEBRUARY 2010

A PRELIMINARY FIELD REPORT BY EEFIT

The M_W8.8 Maule Chile Earthquake of 27th February 2010

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Team photo, taken at the Hotel Diego de Almagro, Talca

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1 Introduction

1.1 Background

The Earthquake Engineering Field Investigation Team (EEFIT) appointed a team of seven members to conduct a reconnaissance mission to the regions of Chile struck by the Mw8.8 earthquake that occurred on the 27th February 2010. The earthquake affected the region known as the Central Valley, the agricultural heartland of Chile, which stretches from just north of Santiago and south to the Rio Biobío which flows through Concepción to the Pacific (see Figure 1-1). The Central Valley lies between the snow covered Andes to the east with peaks up to about 5000m and the Cordillera de la Costa along the Pacific coast which rises up to 500m. The northern parts of the region enjoy a Mediterranean climate, with a prolonged dry season. Rainfall gradually increases towards the south, until around Concepción there is usually rainfall each month.

In addition to the metropolitan region of Santiago the Central Valley encompasses three main administrative regions,

- Region VI – O'Higgins,
- Region VII – Maule and
- Region VIII – Biobío.

1.1.1 Chile's Geography

As shown in Figure 1-1 Chile shares a 5000-km border to the east with Argentina and also borders Bolivia to the northeast and Peru to the north. Chile's population was estimated at 17.1 million in 2010[1], with a growth rate of 1.4%.

There are 13 administrative regions in Chile, each of which is headed by an Administrator who is appointed by the central government; these administrative regions are further subdivided into 40 provinces, each administered by a Governor who is also appointed by the central government. The capital city, Santiago, is located near the centre of the country inland from the Pacific coast, and has a population of about 6.1 million.

Figure 1-1: Map of Chile

1.1.2 Chile's Economy

Chile has a market-oriented economy characterized by a high level of foreign trade. Growth in Gross Domestic Product (GDP) averaged 8% during 1991-97, but fell to half that level in 1998. A severe drought exacerbated the recession in 1999, reducing crop yields and causing hydroelectric shortfalls and electricity rationing, and Chile experienced negative economic growth for the first time in more than 15 years. Despite the effects of the recession, Chile maintained its reputation for strong financial institutions and sound policy that have given it the strongest sovereign bond rating in South America. By the end of 1999, exports and economic activity had begun to recover, and growth rebounded to

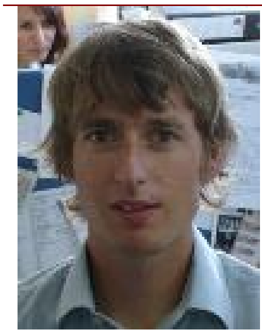
[1] Instituto Nacional de Estadísticas, Chile, Chile: Proyecciones y Estimaciones de Población. Total País 1950-2050. OI No 208

4.2% in 2000, which equated to $70 billion. Growth fell back to 3.1% in 2001 and 2.1% in 2002, largely due to lacklustre global growth and the devaluation of the Argentine peso. Chile's economy began a show recovery in 2003, growing 3.2% and accelerated to 5.8% in 2004. GDP growth benefited from high copper prices, solid export earnings, particularly forestry, fishing, and mining, and stepped-up foreign direct investment.

1.2 The EEFIT Team

The EEFIT team was multidisciplinary, consisting of experts in structural and geotechnical earthquake engineering, seismology, geo-hazards, tsunami, special structures and infrastructure. The team members are presented in Table 1-1.

Table 1-1: The EEFIT Team

			
Zygmunt Lubkowski, Arup	Dr Dina D'Ayala, University of Bath	Dr Adam Crewe, University of Bristol	Ali Manafpour, Consultant
			
Dr Damian Grant, Arup	Tristan Lloyd, UCL	Daniella Escribano Leiva, University of Bristol	Viviana Novelli, University of Bath

1.3 The Mission

The mission took place between the 25 March and the 3 April 2010. Each chapter of this report shows the key cities, towns and villages that were visited during the mission. Due to the wide area that was affected by the earthquake the team split into two groups in order to cover as large an area as possible.

During the mission the team has initiated a number of innovations, with differing levels of success.

- Prior to the mission we obtained high quality post earthquake satellite imagery. This allowed the regions to be investigated to be studied prior to arrival, so we could focus the limited time available.
- Prior to the mission we collated data on damaged areas for international (e.g. EERI; BBC etc) and local sources (e.g. local news and contacts) and posted these to Google Maps. This resource was made available to the team as a way of sharing data gathered prior to arriving in Chile.

- We geo-tagged all photographs, using automatic GPS tracking devices. The purpose is to allow automatic recording of locations in time and space, so photographs can be taken from cars without stopping, vital when travelling on busy roads.
- We have uploaded the most important photographs together with our mission paths to internet systems such as Google Maps or Virtual Disaster Viewer (VDV). This provides a permanent record of the mission which supports this report, which only presents the highlights.
- To aid navigation over such a vast area, satellite navigation aids were used in both cars, to complement traditional road maps, which were at too big a scale. This proved invaluable, especially when unfortunately one of the cars had an accident in the countryside and GPS coordinates allowed the second car to come to the rescue from more than 100km distance.
- We had discussed the potential of writing a blog of the mission. However, a combination of circumstances including the accident, and limited internet service meant this was not achieved. We would recommend that the potential for hosting a blog be investigated by the EEFIT committee prior to the next event, so this option is readily available.

As noted above we were unfortunate to have a serious accident on the 29th March, the first in EEFIT's history. This caused one member of the team to sustain a broken collar bone and the car that four members of the team were travelling in to be written off. This raised a number of important issues, which need to be considered in all future missions.

- It is important that separate teams have an approximate itinerary of each other's schedule for each day. This can be done at the previous nights planning session.
- Communication between teams every few hours (e.g. using simple text messaging) is essential to confirm that everything is progressing to plan.
- The importance of having local knowledge and appropriate language skills. Daniella, the one Chilean national on the team, proved to be an invaluable asset.
- Having a logistics hub in country to organise changes to hotel bookings is vital. This was shown when following the accident we had to amend all subsequent hotel bookings. This was key, as the number of available hotel rooms following the earthquake were limited.
- Making contact with the local British Embassy prior to arrival. This does add a degree of bureaucracy, but it is vital when things go wrong. It is also a good way of promoting EEFIT's activities in diplomatic circles.

1.4 The Report

This report represents the preliminary findings from the earthquake and is aimed as a means to disseminate the factual findings, including photographs and other exhibits. Further research on the findings will be published in due course by EEFIT members in peer-reviewed journals and conference proceedings.

The report is laid out in the form of a travel guide book, with background data (e.g. the local economy, the seismology of the region, the Chilean code etc) and then specific information about the different regions and towns that were visited. Where appropriate, maps are provided showing town layouts and the locations of surveys undertaken by the teams and/or key structures that have been investigated. As noted above this report is supported by a library of images which will be available on the EEFIT website.

1.5 Acknowledgements

- Berenice Chan and Dr Tizianna Rosetto who provided logistical support to the mission from London.
- Miryam Mallea at BGC Engineering Inc in Santiago, who ensured all our hotel bookings were made and altered as circumstances changed.
- Tom Wilcock and his colleagues at the British Embassy in Santiago.

- Professor Saragoni and Professor Moroni at the University de Chile in Santiago.
- Dr. Gianmario Benzoni, Research Scientist University of California San Diego.
- Laura Kong, Ricardo Norambuena and Emilio Lorca from UNESCO / International Tsunami Information Centre who provided valuable information and guidance for the tsunami affected region. They also facilitated knowledge sharing between other international teams through their Chilean tsunami online collaboration system, Basecamp.
- The Chilean Air Force, for allowing Tristan Lloyd to accompany them on an aerial overview flight over the majority of the tsunami inundation zone.
- Ruben Escribano (Daniella's Father) for his help with logistics around Concepción.
- AIR Worldwide Ltd, Arup Ltd, Aon Benfield, British Geological Survey, CREA Consultants, Risk Management Solutions and Sellafield Ltd. who all sponsor the work of EEFIT.

2 Seismological Aspects and Code Requirements

2.1 The Maule Earthquake

The Maule Chile earthquake of 8.8M_w occurred at 06:34:14 UTC on the 27th February 2010 at a depth of 35 km (USGS). It ruptured at the boundary between the subducting Nazca and South American tectonic plates which are converging at a rate of 80 mm per year (see Figure 2-1). The present event which was centred some 65 miles west-southwest of Talca, and 200 miles southwest of Santiago, and has a rupture zone of approximately 500-600 km. Figure 2-2 shows the surface projection of the slip distribution and the position of aftershocks greater than 5M_w up to 2nd March 2010. A large number of aftershocks (458 up to the 29th March 2010) have been recorded since, with the largest being a 6.9M_w event on 11th March 2010, striking north of the main event but closer to shore.

The earthquake also triggered a tsunami whose waves hit the Chilean coast and also travelled to Peru and westward past Hawaii, to Japan and New Zealand.

The earthquake affected more than 2 million people, but notwithstanding the magnitude of the event, both number of major structural collapses and a relatively low death toll of 507 is a key characteristic.

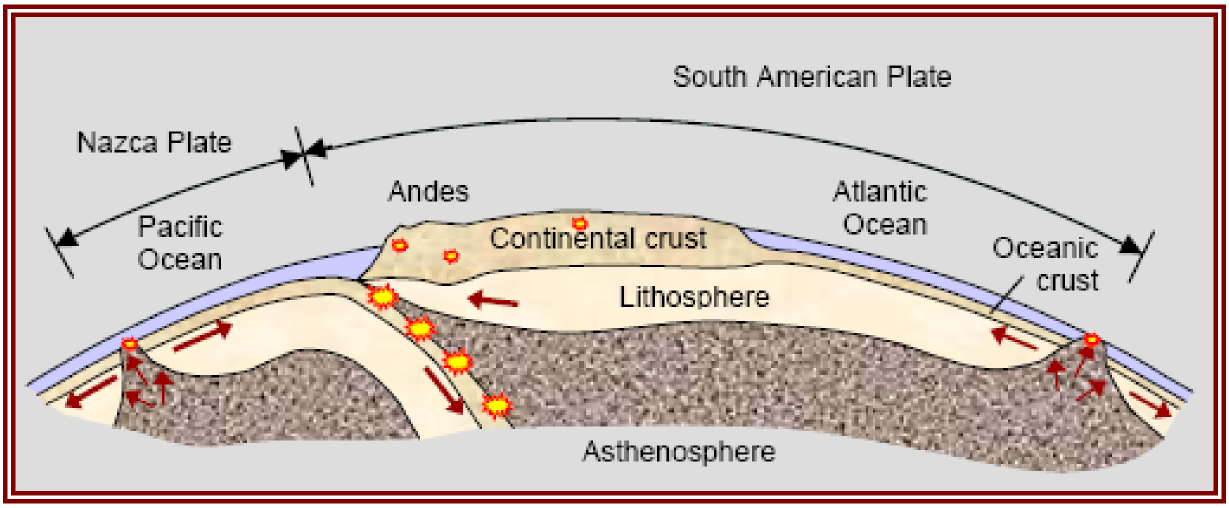


Figure 2-1: Schematic W-E Section through South America and Typical Subduction Processes (Arup, 1992)

Chile is located on the Pacific Ring of Fire and is one of the most seismically active countries in the world. On the 22nd May 1960 the largest instrumentally recorded event occurred off the west coast of Chile, with a magnitude of 9.5M_w. The 8.8M_w Maule earthquake, is the second strongest in the recorded history of Chile.

Major earthquakes occur on the boundary between the subducting Nazca Plates, whilst smaller events occur within the continental crust of the South American Plate, as is shown in Figure 2-1. There are two principal subduction earthquake types, namely intraslab and interface earthquakes. An intraslab earthquake is one which occurs within the subducting plate, whilst an interface earthquake occurs at the boundary between the subducting plate and the continental crust. Interface earthquakes give rise to the world's biggest earthquakes, which are known as megathrust earthquakes. The Maule earthquake was one of these megatrust earthquakes.

Dr. Ben Brooks and Dr. James Foster at the University of Hawaii have determined a preliminary solution for the coseismic displacement field associated with the recent M 8.8 Maule earthquake in south-central Chile (Figure 2-3). Peak measured displacement is 3.04 m near the city of Concepción, Chile. Significant displacements are evident as far east as Buenos Aires, Argentina (2-4 cm) and as far north as the Chilean border with Peru.

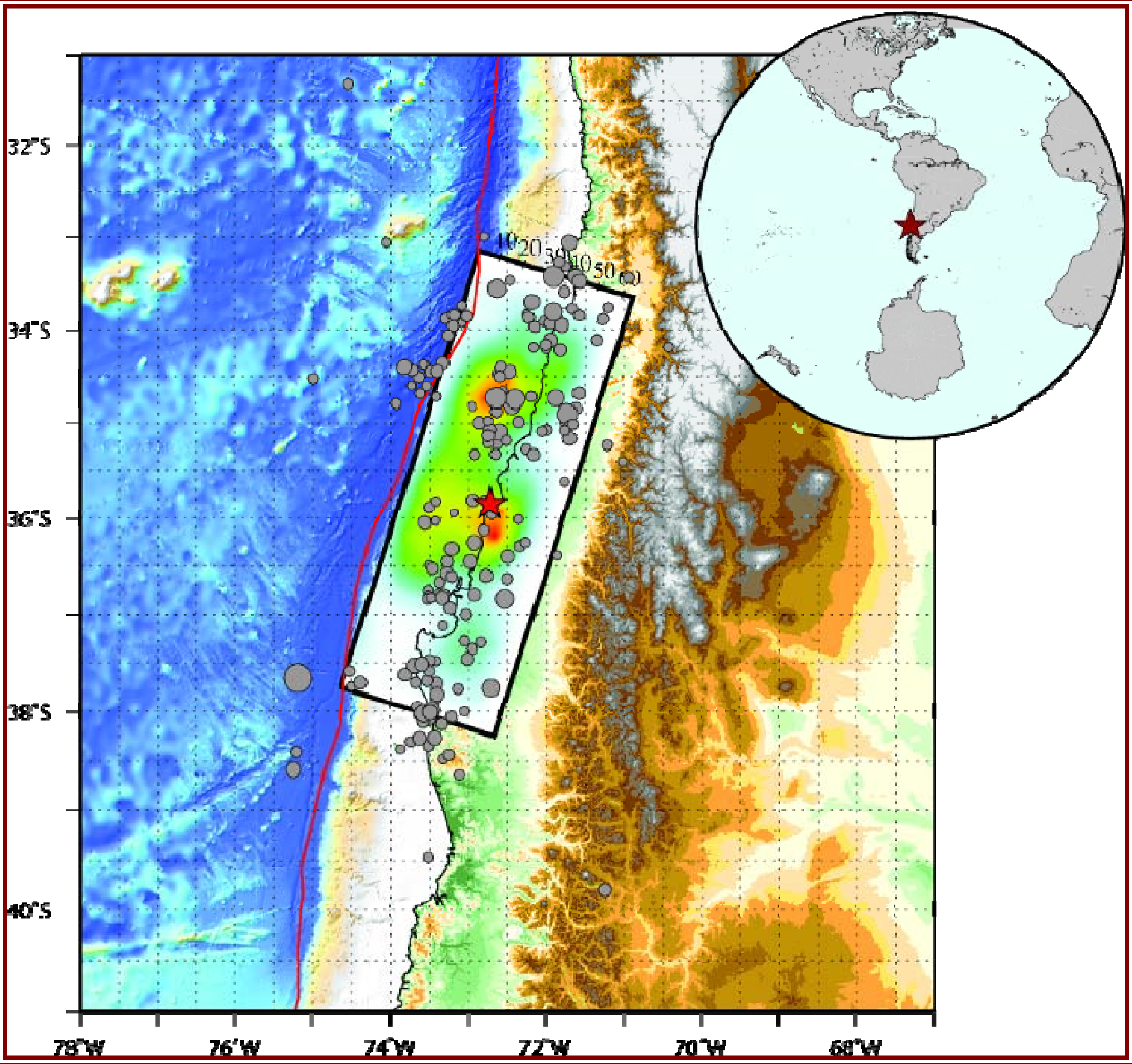


Figure 2-2: Surface projection of the slip distribution (downloaded from USGS http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/finite_fault.php)

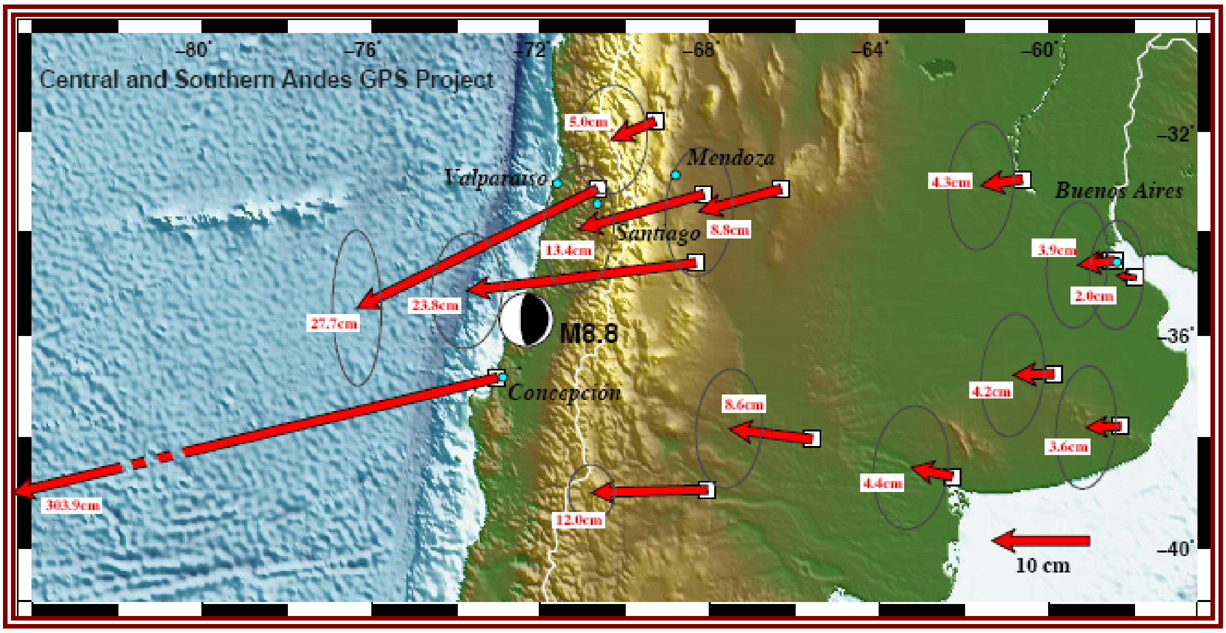


Figure 2-3: A zoomed in view of the preliminary solution for the coseismic displacement field associated with the recent M 8.8 Maule earthquake in south-central Chile, (downloaded from http://www.unavco.org/research_science/science_highlights/2010/M8.8-Chile_EQ_zoom.pdf)

2.2 Strong Motion Records

In order to better understand the context of the shaking effects on the built environment, Table 2-1 and Table 2-2 report the preliminary horizontal and vertical peak ground acceleration (PGA) values of nine strong motion records as processed by the Universidad de Chile Departamento Ingenieria Civil and four records as processed by the Seismological Survey. Data on soils are not yet confirmed and influence of nearby structures or soil structure interaction' effects have not yet been evaluated. Preliminary information suggests that the shaking lasted 140 s, with the strong phase lasting between 40 and 60 sec.

Table 2-1: Maximum accelerations reported by U de Chile (accessed at http://www.renadic.cl/red_archivos/UdeCHILE_Informe_EQ_20100227_Ing_Civil_Inf_4_Ver_1.pdf)

Station	Maximum horizontal PGA (g)	Vertical PGA (g)
Santiago, UdeCHILE (inside building)	0.17	0.14
Santiago, Metro Station Mirador	0.24	0.13
Maipu CRS RM	0.56	0.24
Tisne Hospital RM	0.30	0.28
Sotero de Rio Hospital RM	0.27	0.13
Curicó Hospital	0.47	0.20
Valdivia Hospital	0.14	0.05
Viña del Mar (Marga Marga)	0.35	0.26
Viña del Mar (Centro)	0.33	0.19

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Table 2-2: Maximum accelerations reported by Seismological Survey (accessed at http://ssn.dgf.uchile.cl/informes/INFORME_TECNICO.pdf)

Station	Horizontal PGA (g)		Vertical PGA (g)
	NS	EW	
Colegio San Pedro, Concepción	0.65	0.58	0.60
Cerro Calán, Santiago	0.20	0.23	0.11
Campus Antumapu, Santiago	0.23	0.27	0.17
Cerro El Roble	0.19	0.13	0.11

All these records are uncorrected, and the U de Chile expresses some doubt about the high value recorded in Maipu. The Maipu response spectra are reproduced in Figure 2-4 and are compared to the Code spectrum. It appears that this may be a local site effect, but further work will be necessary to confirm this issue.

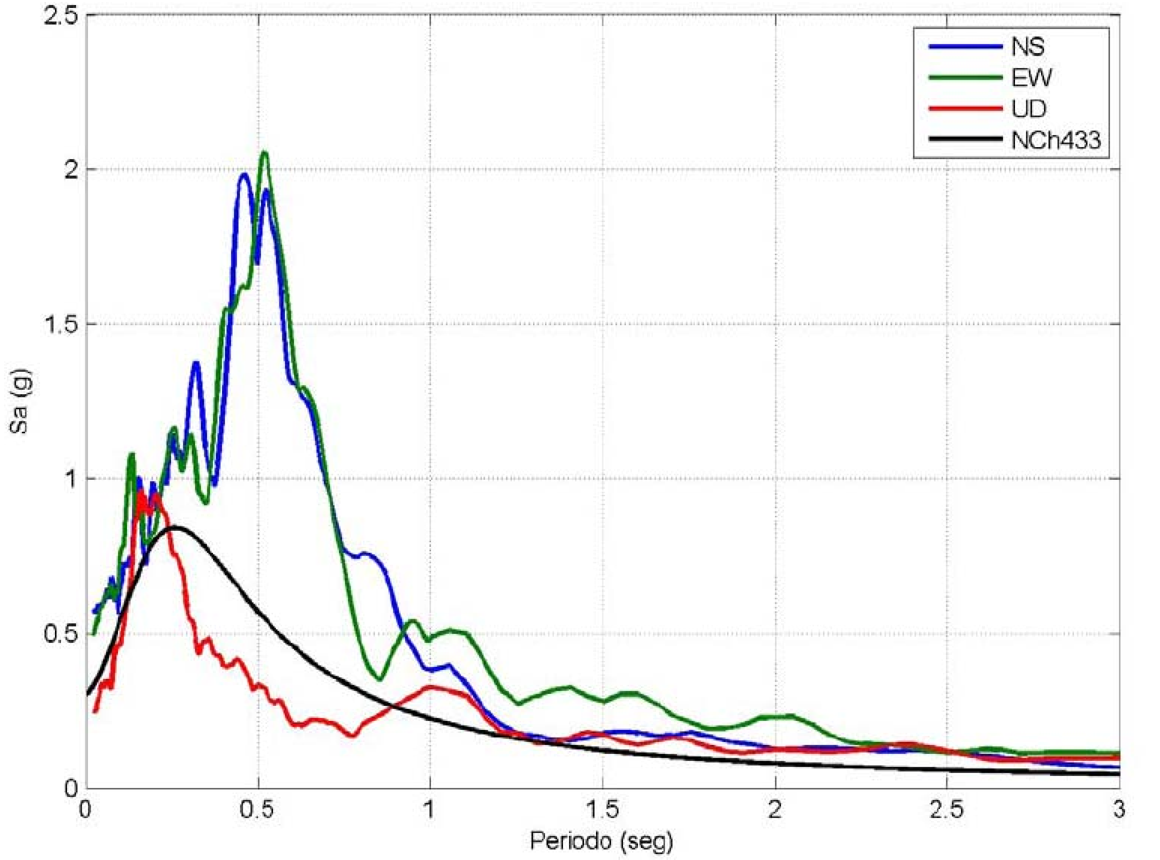

Figure 2-4: Response Spectra for Maipu Strong Motion Records

The maximum ordinate of the design spectrum is approximately 0.85 g. (in black in Figure 2-4). It should be noted that, in the period range 0.3 to 0.5 sec., all response spectra, except for the records in Santiago and in Valdivia, show values of maximum amplification of the horizontal motion, substantially greater than the corresponding design spectrum of the Chilean Code.

The measured PGA values have been compared to a range of different ground motion predictive models (e.g. Atkinson & Boore, 2003; Zhao, 2006; Youngs et al, 1997; McVerry et al, 2006 and Ruiz & Saragoni et al, 2005) appropriate to interface subduction events. The comparisons are shown in Figure 2-5. Generally the measured values appear to exceed the equations for rock, but agree well with the equations for deep soil sites. A similar comparison should be carried out for other spectral periods.

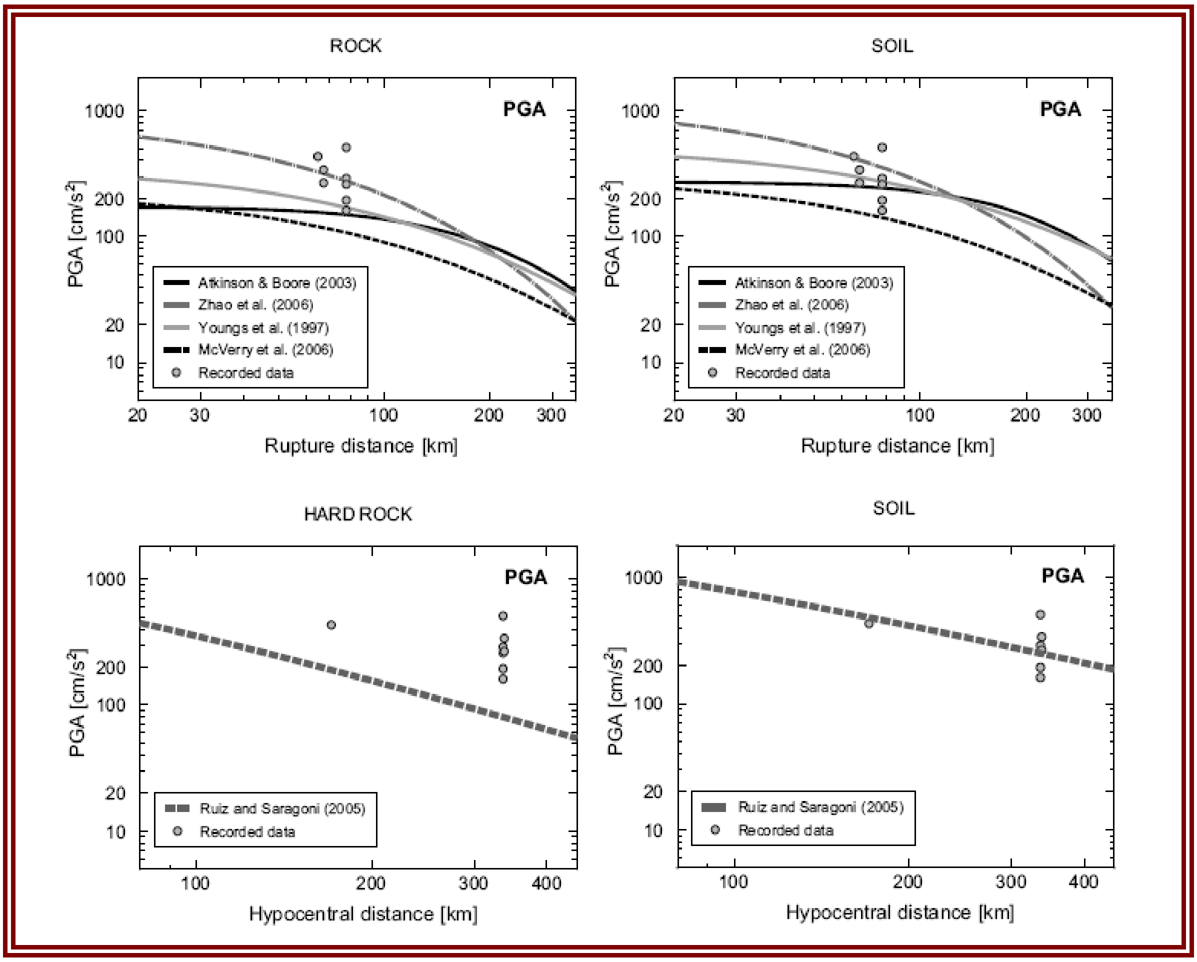

Figure 2-5: Ground Motion Models

2.3 Intensity

The earthquake was felt on land as far north as Peru and eastward as far as Sao Paolo, in Brazil. Figure 2-6 shows the estimated macroseismic intensity map developed by the USGS using their PAGER system. The USGS Shakemap and Pager programmes provide an almost immediate estimate of shaking macroseismic intensity and exposed population by intensity level as can be seen in Figure 2-6. This helps identify the most severely hit areas and hence to tailor post-event emergency and reconnaissance accordingly.

In the following chapters, for each region and locality visited by the EEFIT team estimates of observed EMS intensities are tabulated.

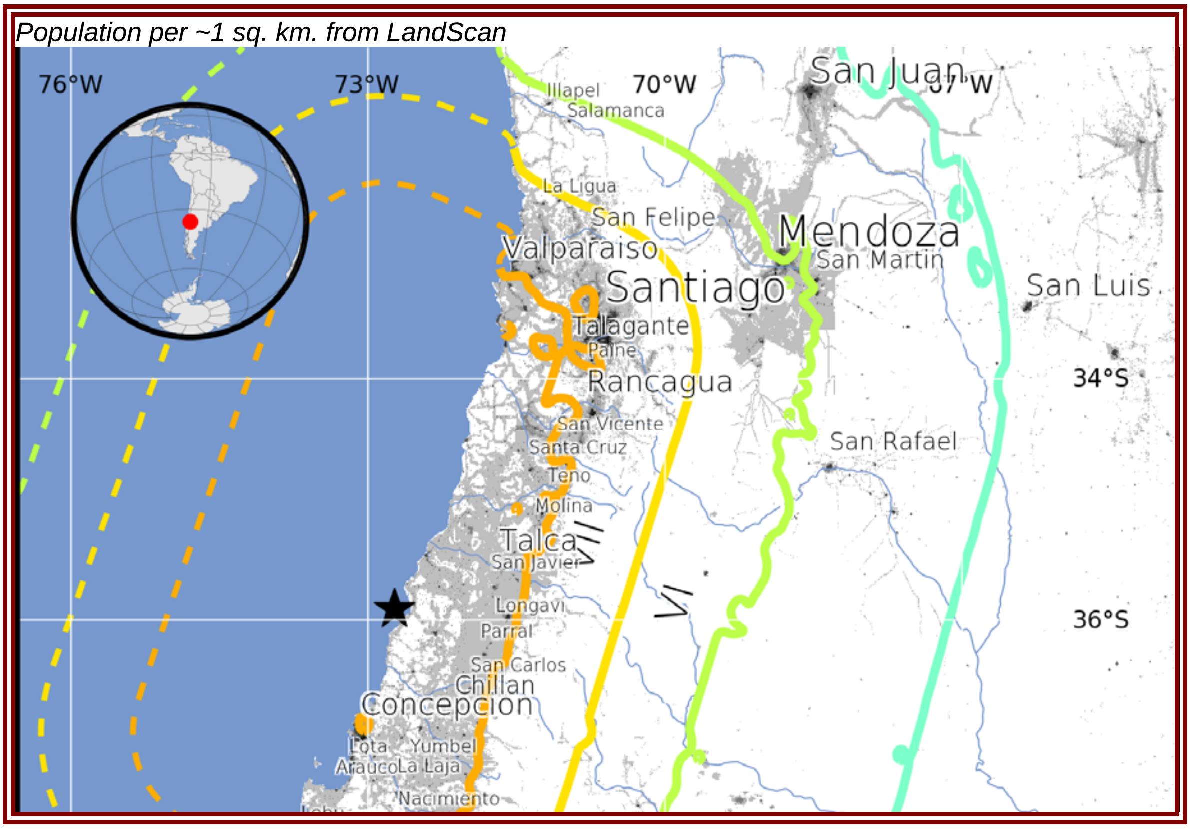

Figure 2-6: Population exposed and Macroseismic Intensity maps and exposed cities (From PAGER accessed http://earthquake.usgs.gov/earthquakes/pager/events/us/2010tfan/index.html)

2.4 The Chilean Seismic Code

The history of the Chilean seismic regulations goes back to 1928. In that year the city of Talca was affected by an earthquake and, as a result, in 1929 the government passed a law creating a committee to propose earthquake related regulations. Then, in 1935 a building code known as Ordenanza General de Construcciones y Urbanizaciones became official. The Chillan earthquake of 1939 prompted the government to appoint several committees to study the current seismic codes and propose modifications. These modifications went into effect officially in 1949. In 1958 another earthquake rocked the country, prompting a review of the current design practices. A government body known as INDITECNOR, which eventually changed its name to Instituto Nacional de Normalización (INN), started reviewing the design practices of the Ordenanza. Finally, in 1972, a seismic code known as Calculo Antisismico de Edificios (Earthquake Design of Buildings) was officially approved. A second edition of this seismic code was published in 1985 (INN 1985). The most recent version of this code, also known as Diseño Sismico de Edificios (INN 1996), is currently used in Chile.

The code divides the country into three seismic zones, 1, 2 and 3. Figure 2-7 shows the zoning in the region affected by the earthquake. The seismic coefficient (Ao) for each of these zones is 0.2g, 0.3g and 0.4g respectively.

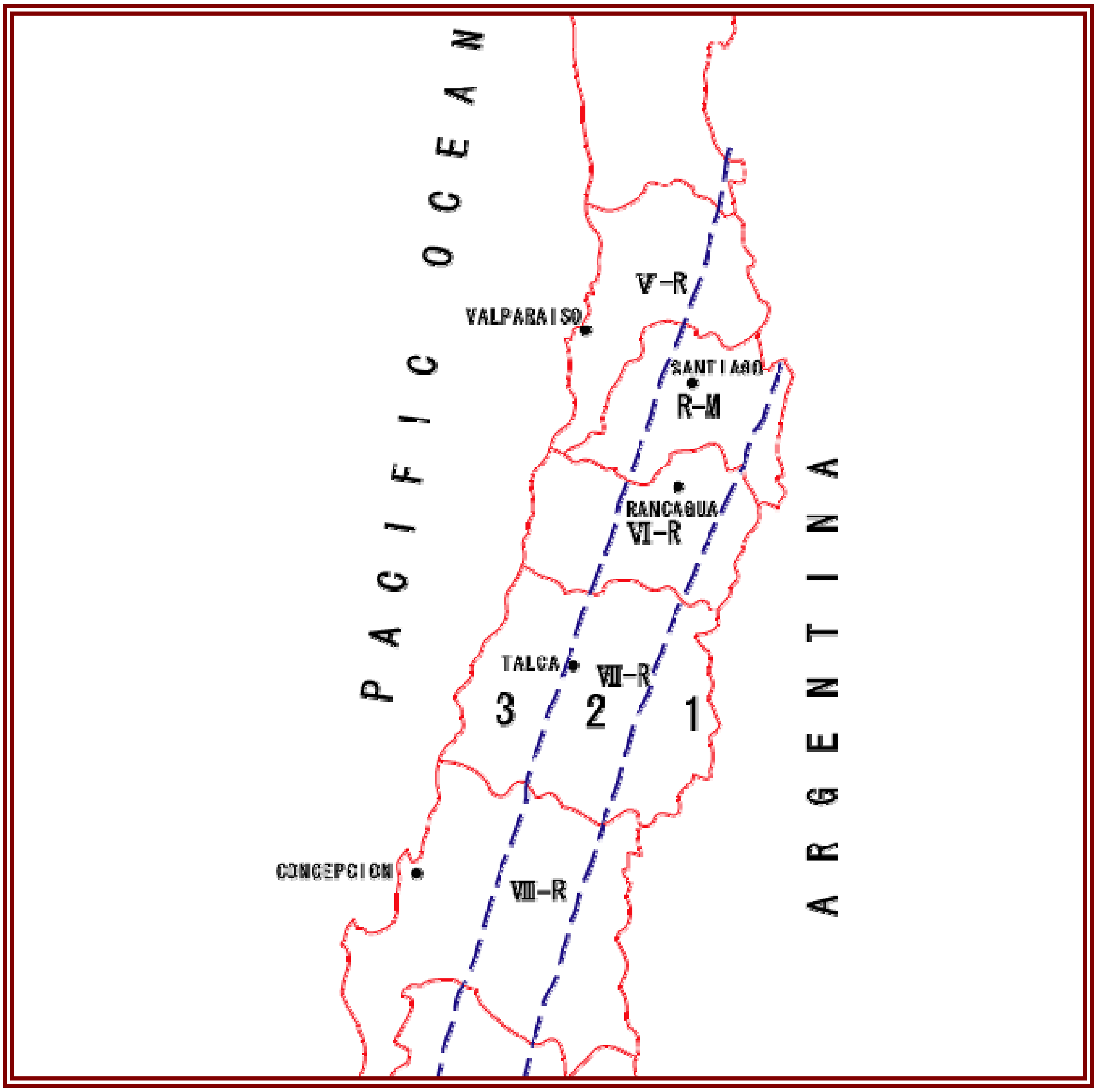

Figure 2-7: Seismic zoning of Regions V, VI, VII, VIII and Metropolitan

The code identifies four soil types as shown in Table 2-3. The seismic parameters corresponding to each of these soil types is given in

Table 2-4.

Table 2-3: Soil Type according to Chilean Code NCh 433.Of96

Soil Type	Definition

Soil Type	Definition
I	Rock, with shear wave propagation > 900 m/s. $S_u \geq$ 10MPa and RQD ≥ 50%
II	1) $V_s \geq$ 400 m/s in the first 10 m. and increasing with depth 2) Dense gravel, $\gamma_d \geq$ 20 KN/m^3 or DR ≥75% 3) Dense sand DR > 75% or normalized N_{SPT} > 40 4) Cohesive dense soil $S_u \geq$ 0.10MPa, $q_u \geq$ 0.20Mpa without fissures. Minimum thickness of the layer must be 20 m. It the thickness of the layer above the rock is less than 20 m. the soil will be classified as I.
III	1) Non saturated sand with DR between 55% and 75%, normalized N_{SPT} < 20. 2) Saturated gravel or sand compaction < 95% of Modified Proctor. 3) Cohesive soil with S_u between 0.025 and 0.10 MPa. (q_u between 0.05 and 0.20 MPa) independent of water table depth. 4) Saturated Sand with normalized N_{SPT} between 20 and 40. Minimum thickness of the layer must be 10 m. If the thickness of the layer is less than 10 m. the soil will be classified as II.
IV	Saturated cohesive soil with $S_u \leq$ 0.025 MPa.($q_u \leq$ 0.050 MPa). Minimum thickness of the layer must be 10 m. If the layer of the soils I, II or III is less than 10 m. the soil will be classified as III.

Table 2-4: Parameter values related soil types NCh 433.Of96

Soil type	S	T_o (s)	T' (s)	*n*	*P*
I	0.90	0.15	0.20	1.00	2.0
II	1.00	0.30	0.35	1.33	1.5
III	1.20	0.75	0.85	1.80	1.0
IV	1.30	1.20	1.35	1.80	1.0

The base shear (Qo) is defined using the following equation:

$$Q_0 = CIP$$

where C: coefficient given by the following formula.

$$C = \frac{2.75 A_0}{gR}\left(\frac{T'}{T^*}\right)^n$$

n, T': Parameters related to the foundation soil type (See Table 2-4)

Ao: Maximum effective acceleration (See Figure 2-7)

I: Coefficient of importance (See Table 2-5)

R: Reduction factor (See Table 2-6)

T*: Period of mode with the highest translational equivalent mass in the direction of analysis.

P: Total weight of the building above base level.

Table 2-5: Importance Factor

Building Category	Description	P

Building Category	Description	P
A	Governmental, municipal, public service or of public use (such as police stations, power plants and telephone exchanges, post offices and telegraphs, broadcasting stations, television channels, waterworks and pumping stations, etc.), and those whose use is of special importance in the event of a catastrophe (such as hospitals, first aid units, fire stations, garages for emergency vehicles, terminal stations, etc.).	1.2
B	Buildings whose content is of great value (such as libraries, museums, etc.) and those which frequently receive a great number of people: - assembly rooms for 100 people or more; - stadiums and bleachers for 2000 people or more; - schools, nursery schools and university buildings; - prisons and detention precincts; - commercial stores with an area equal to or greater than 500 m2 per floor, or more than 12 m in height; - shopping malls, with a total area greater than 3000 m2 ,not including the parking lot.	1.2
C	Buildings intended for private or public use that do not belong to category A or B, and constructions of any type, whose failure may jeopardize other constructions classified as A, B or C.	1.0
D	Isolated or provisional structures not intended for living and which cannot be classified in any of the aforementioned categories.	0.6

Table 2-6: Maximum values of Reduction factor

Structural system	Structural material	*R*	R_o
Space moment-resisting frames	Structural Steel	7	11
	Reinforced Concrete	7	11
Shear walls and braced systems	Structural steel	7	11
	Reinforced Concrete	7	11
	Reinforced Concrete and Confined Masonry		
	- If criterion A is met	6	9
	- If criterion A is not met	4	4
	Wood	5.5	7
	Confined Masonry	4	4
	Reinforced Masonry		
	- Of concrete blocks or units of similar geometry with full grouting and double-width masonry.	4	4
	- Of clay bricks with partial or full grouting and concrete blocks or units of similar geometry which have partial grouting.	3	3
Any type of structure or material that cannot be classified in one of the above categories.		2	

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3 Santiago and the Surrounding Region

3.1 Background

The main cities and towns that were visited by EEFIT in the north of the earthquake-hit region included Santiago, Valparaíso and Viña del Mar. EEFIT came to this region following the 1985 earthquake, whose epicentre was near Valparaíso. The report for that event is available at www.eefit.org.uk, and provides useful background information.

Figure 3-1 shows the region, the areas visited by the EEFIT team. The following paragraphs provide a brief overview of each location and their building stock.

Figure 3-1: Santiago & Regions

Santiago – This is Chile's cultural and economic capital, with a population of 6 million, and was founded in 1541. It lies on the Rio Mapocho in a natural bowl surrounded by mountains. It was destroyed by earthquakes in 1647 and 1730. In the later part of the 20th century Santiago has grown rapidly. Generally the more affluent regions are in the east of the city and the poorer areas are to the west. It is a mix of modern high rise buildings, older low rise confined masonry construction. There is an extensive road network, including a motorway network, which passes both through and around the city leading to a high level of air pollution. There is also a new subway system and Chile's major international airport lies about 12km north-east of the city centre.

Valparaíso – Founded in 1542 it developed into the South Pacific's most important port. The opening of the Panama Canal in 1914, the great depression in the 1930s, the building of the San Antonio container terminal and the shift of banks to Santiago has lead to its decline. It suffered a devastating earthquake in 1906, which destroyed most of the old colonial buildings. Despite this decline it is still one of Chile's major economic centres, with major port operations and agricultural operations producing in particular soft fruits, such as avocadoes, tomatoes and peaches. Its current population is about 300,000.

Viña del Mar – Nine kilometres north-east of Valparaíso lies Viña del Mar, one of South America's leading tourist resorts. The older part is situated on the banks of the creek, Marga Marga, but most of the older buildings have not resisted the effect of earthquakes or bulldozers.

Figure 3-1 shows the region, and the areas visited by the EEFIT team.

3.2 Observed Intensities

Table 3-1 presents an estimate of the EMS intensity for the based on the observations, surveys and discussions with locals. More specific information about specific points of interest is provided in the following sections.

Table 3-1: Observed Intensities Metropolitan Region

City/town	Distance from the epicentre (km)	Region	Population	EMS
Santiago	400	Metropolitana	5.428.590	7
Valparaiso	540	Valparaiso	803.683	7
Viña del Mar	549	Valparaiso	286.931	7

3.3 Historical and Vernacular Buildings

The Architectural Heritage of Chile is managed and overseen by the Consejo Nacional de la Cultura y las Artes, and cared for by the Centro Nacional de Conservacion and Restauration.
On 25th March 2010, the CNCA issued a preliminary list of assessment of damage to all churches at national level. Of the total 437 churches with damage, 19% were classified as collapsed or scheduled for demolition, 24% with serious structural damage, probably repairable, 25% with repairable considerable damage, and 32% with repairable damage, for a total estimated damage cost of 140.billion of Chilean pesos. (http://www.iglesia.cl/breves_new/archivos/20100325_catastro.pdf)
In the last week a classification of damage to National Monument and Typical Zones affected by the earthquakes by region has also been compiled and the summary data is reproduced in Table 3.2. (http://www.monumentos.cl/OpenDocs/asp/pagDefault.asp?boton=Doc51&argInstanciaId=51&argCarpetaId=305&argTreeNodosAbiertos=(0)(305&argRegistroId=3823)

Table 3-2: Observed Damage to Historic Monuments and Typical Zone by region, as surveyed to the 27/05/2010, prepared by Área de Planificación y Estudios Consejo de Monumentos Nacionales

REGION DANOS	METROPOLITANA	VALPARAISO	LIB. GRAL. BDO OHIGGINS	MAULE	BIOBIO
No Catastrados	145	22	11	1	11
Sin Daños	16	34	3	8	5
Destruidos	0	0	0	1	0
Menores	36	26	3	3	5
Regulares	31	21	9	5	3
Mayores	13	14	23	24	11
TOTAL MHI y ZT	**241**	**117**	**49**	**42**	**35**

In Santiago a relatively large number of important historic and heritage buildings were damaged by the earthquake (Area Metropolitana), although the majority have not been surveyed yet. The EEFIT team observed two major cases of partial collapse: the bell tower of the Iglesia de la Providencia and the top portion of the south eastern chapel of the Basilica del Salvador.

Of the 174 churches and chapels in Santiago, listed in the document summarised in Table 3.2, two are scheduled for demolition, 43 (25%), have been assigned serious structural damage probably repairable, 41 (23%) with repairable considerable damage, while the rest with repairable damage, and the remaining 51% with repairable damage.

The list of buildings visited and level of damage observed in each of them is shown in Figure 3-2 were the location of the visited building within Santiago is also shown. Damage ranged from partial collapse (in red) to structural damage (in purple) to damage to architectural finishes or very localised collapse (in yellow).

The worse case is represented by the collapse of the upper part of front bell tower of the Iglesia de la Providencia, in the Providencia district of Santiago, on the main thoroughfare which crosses the city east-west.

The church, shown before and after the event of 27 February 2010 in Figure 3-3, was built between 1881 and 1890 to a design by the Italian architect Eduardo Provasoli, in neo renaissance style. The church occupies one of the sides of the plot which host the remains of a partially enclosed two-storey cloister, which was once part of an orphanage called Casa Nacional del Nino, run by the congregations of nuns of the Providencia. This church has been catalogued as a national monument since 1989.

The façade, as in other cases surveyed in Santiago, is built in brickwork, while the roof and vaults of the main nave are made of a composite of timber and plaster, which is lighter than masonry vaults. The upper part of the church nave was not accessible and hence was not possible to inspect accurately to which extent the façade is connected to the rest of the structure, but from other examples visited, it would appear that the façade is rather independent. This is also confirmed by the very modest level of damage seen in the interior.

Damage is instead evident at the keystones of the vaults forming the front portico, notwithstanding the presence of transversal anchors. No evidence of pullout of the anchors from the masonry could be observed. Vertical cracks were also observed in the apse, severing this form the main body of the church. Apart from the loss of the top of the bell tower the rest of the damage was of level DG2–DG3 (EMS ’98).

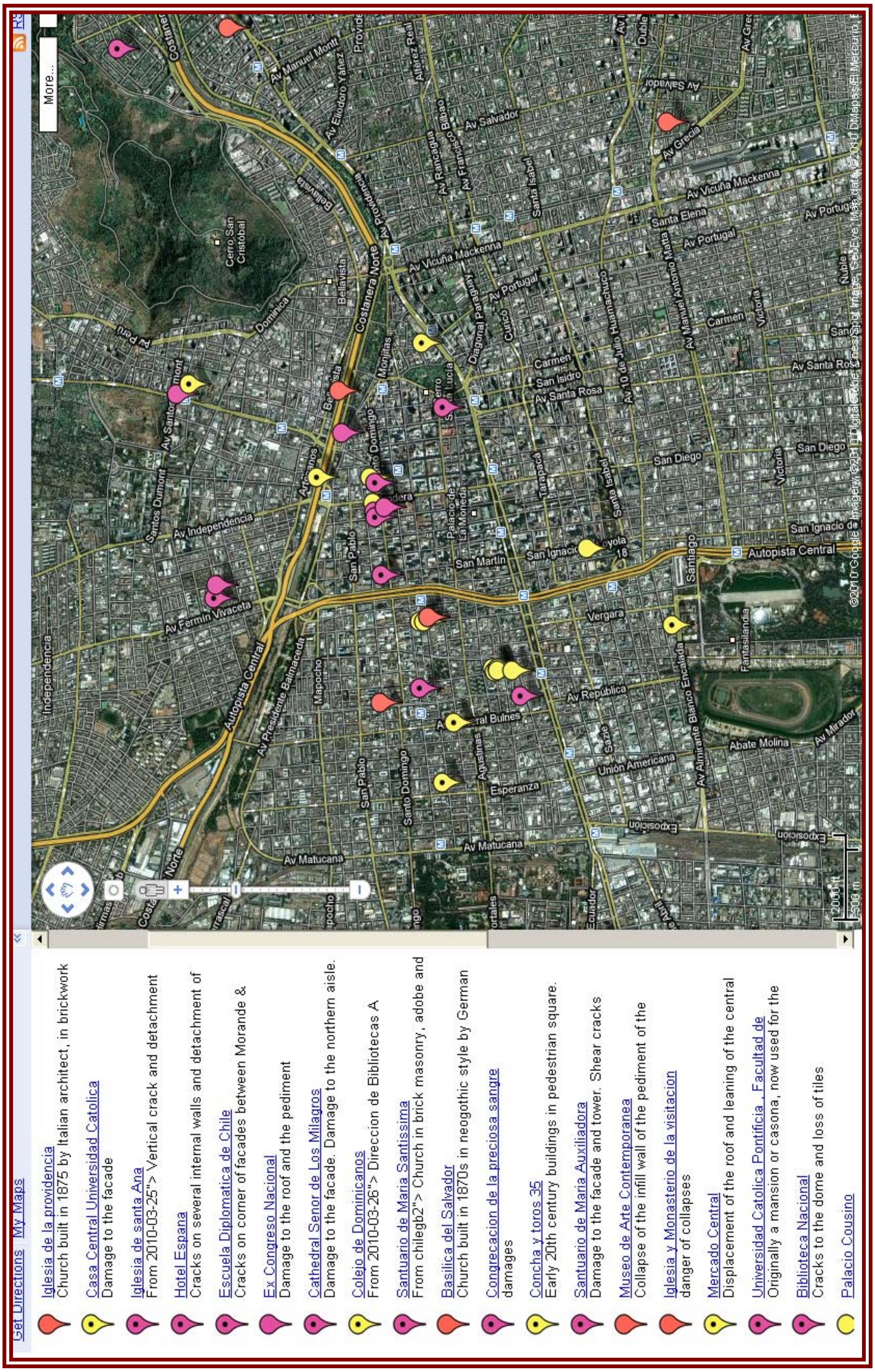

Figure 3-2: Interactive map of historic sites visited in Santiago, 26 to 31st March 2010

http://maps.google.co.uk/maps/ms?ie=UTF8&hl=en&t=h&msa=0&msid=202196774376856840187.00048346ed9539d12f9a2&z=13

Figure 3-3: Iglesia de la Providencia: Façade elevation before and after the earthquake. The cap of the bell tower has been lost.

Figure 3-4: Interior corner between façade and south wall of the nave. A crack of separation between the two walls is visible. In the portico a longitudinal cracks runs through all keystones of the vaults supporting the tower. However no lateral permanent sway of the springs is detectable.

A second church of the same period, whose construction began in 1870 in neogothic style by the German architect Teodoro Burchard followed by Chilean Architect Josué Smith Solar, is the Basilica del Salvador. This is one of the largest religious buildings in Santiago with a length of 100 metres and a height of 30 metres, design to accommodate up to 500 people. The construction took more than 60 years to complete and materials and finishes vary from the back of the church to the front. Brickworks set in mud mortar in the apsidal area, while stone set in lime mortar constitutes the façade. The church is sited in the Barrio Brasil, a wealthy neighbour in the 1920s, nowadays considered a bohemian district. The church was catalogued as an historic monument in 1977, but had already been neglected for some years when it was severely damage by the Valparaiso earthquake of 1985.

In Figure 3-5 the façade and southern elevation with signs of neglect and partial reconstruction following the 1985 earthquake are shown. The south façade had been propped and the building cordoned off for a long time prior to the earthquake. The damage caused by the latest event is recorded in Figure 3-6.

Figure 3-5: Western and southern elevation of the Basilica del Salvador

Masonry around the opening at the connection between the façade and the south elevation was lost together with material at connection between the south elevation and the apsidal area.

Figure 3-6: Loss of material at the intersection between façade and southern elevation where there is an abrupt change in stiffness. The missing portion of the south east chapel fell as a solid boulder.

The configuration with one or two towers on the front façade is common to many churches in Santiago, and damage to the towers to different degrees was recorded in many instances. The main other damage observed was detachment of the façade from the rest of the church. Examples are included in Figure 3-7 for other three buildings in different locations in Santiago and in Valparaiso. These two mechanisms represent well known major vulnerabilities of church like masonry structures and have been codified following the Friuli, Italy earthquake 1974 and Umbria–Marche, Italy earthquake 1997.

Figure 3-7: a) Twin bell towers in brickwork and timber of the Maria Santissima Sanctuary, damage in the columns and leaning of the timber structure of the left tower. b) Church off Enrique Mac Iver, shear failure at the base of the spire. c) Church of convent of San Francisco in Valparaiso. The convent was initially set in 1845 and the church in 1851 completed with the façade, also by Edoardo Provasoli, in 1890. Was declared national monument in 1983 and partially destroyed by a fire in the same year. It shows vertical cracks over the façade arches and cracks at the base of the tower. Damage to the arches more pronounced than in the case of the Providencia.

Besides the churches other typical major heritage type buildings are represented by old hacienda type houses and by convents. These two categories have very similar structural types. They are composed of a series of rooms in a line set around a court yard. The walls are made of adobe, in the best cases set over a base of regular masonry up to 600 mm off the ground. The rooms are usually sheltered by porticoes made of timber post supporting a timber canopy. This structural arrangement is also found in minor vernacular historic construction with similar but poorer construction details and materials. Among the ones visited is worth mentioning the ex Convent of the Dominicans which now hosts the Centro Nacional de Conservacion and Restauration and the old mansion that hosts the 116 years old Faculty of Architecture of the Universidad Pontificia de Chile.

The first building has been restored and strengthened for the past 5 years. The strategy was to improve weather-tightness and resilience of the adobe walls by plastering them using a layer 10 mm thick of lime-based mortar held by chicken wire mesh. However the bonding between the plaster and the adobe was very poor and most internal and external walls completely lost it, This created substantial disruption to work and damage of some equipment, although no structural damage was visible (Figure 3-8) The annex church of Recoleta Dominica, built in brickwork with mud mortar had suffered important damage in the 1985 earthquake. The defacing strengthening and repatching carried out using concrete admixture and concrete ring beams are visible on the masonry fabric.

Figure 3-8: Convento de Dominicani and Recoleta Dominica church

The Architectural Faculty building suffered more serious damage, with numerous through-depth cracks in perimeter and spine walls and one partial collapse. The most severe damage was in locations that had already been repaired after the 1985 earthquake using epoxy resins or concrete mixture with reinforcement and where they had been strengthened with shotcreting. Although some areas had been cordoned off and helmets had been distributed to staff, the majority of the rooms were open and with full student occupancy.

Minor damage to architectonic finishes was observed in many other heritage buildings, from the Museum of Contemporary Arts and the Parliament (both had damage in their pediments and roofs) to many museums and some of the older buildings of both Universidad de Chile and Universidad Catolica Pontificia.

Figure 3-9: The faculty of Architecture of the Universidad Pontificia Catolica de Chile. The school of architecture, first set in 1894, is hosted in mansion buildings of the mid 19th century re-adapted for institutional use.

3.4 Modern Buildings

Many modern buildings in Santiago, Viña del Mar and Valparaiso performed well under the earthquake shaking showing only minor or superficial damage. However, in some areas the team visited there was moderate to significant structural damage to modern buildings.

3.4.1 <u>Viña del Mar and Valparaiso</u>

A common cause of failure in reinforced concrete shear wall buildings was buckling of longitudinal reinforcement in boundary zones of slender walls. One example was the 15-storey Edficio Festival, near the waterfront in Viña del Mar (Figure 3-10). Failure of external shear walls at ground level is shown in Figure 3-10 (middle and right). Note that the boundary zones were heavily reinforced with longitudinal reinforcement, but that the transverse reinforcement appeared to be inadequate. The stairwells also experienced severe damage (Figure 3-11).

Figure 3-10: Edificio Festival, Viña del Mar, and damage to shear wall boundary zones

Figure 3-11: Edificio Festival, Viña del Mar, damage to stairwells

Another example of buckling failure in shear walls is shown in Figure 3-12. In this case, buckling was severe, and the building was propped over the entire basement level.

Figure 3-12: Propping due to severe buckling in boundary zones of shear walls

Several apartment buildings on the waterfront in Viña del Mar also suffered damage. The 15-storey waterfront apartment building shown in Figure 3-13 appeared to be a mixed reinforced concrete shear wall and moment frame system. There was evidence of damage at the base of shear walls (Figure 3-13, middle) and at beam-column joints (Figure 3-13, right). Internally, there was also evidence of punching shear failure (Figure 3-14, left) and damage to shear walls and ceilings (Figure 3-14, right).

Figure 3-13: Waterfront apartment building, Viña del Mar, external damage

Figure 3-14: Waterfront apartment building, Viña del Mar, internal damage

3.4.2 Santiago

Damage to modern buildings in Santiago did not appear as severe as in the coastal cities of Viña del Mar and Valparaiso. A residential apartment block in Maipu district, southwest of the Santiago, had suffered major structural damage (apparently due to a soft storey mechanism). The building was constructed with a reinforced concrete structural wall system. The five storey building appeared to have an open storey at the ground level except at one end of the building. Access to the building area was restricted by the authorities and a close inspection was not possible at the time of the visit. However it was clear that the far end of the building (see Figure 3-15) had partially or totally lost its ground storey. This had caused a collapse mechanism with longitudinal and vertical distortion of the building.

Another building block with a similar structural system collapsed with partial soft storey failure mechanism at the ground level. Figure 3-16 shows the general views of the building and the details of the damage to structural system can be seen in Figure 3-17. It is evident that slender columns (walls) have not been able to produce sufficient strength and stiffness at the point of irregularity between two adjacent floors. While the exact cause of damage and partial collapse of these few buildings among other similar buildings remains to be investigated, from our observations some signs of poor concreting were identified and recorded.

Figure 3-15: Damaged apartment block in Maipu district (Tristan Valdes), Santiago, general views and detail of the damage at the connection of two parts of the building with different ground floor structural system.

Figure 3-16: Another damaged apartment block in Maipu district, Santiago (general views)

Figure 3-17: Details of the damage to the ground floor of the apartment block in Figure 3-16

Another part of the city with modern buildings which showed significant damage in the earthquake was located in the north eastern suburb of Santiago, Ciudad Empresarial. The area is well developed with several modern buildings. Francisco Medina from the EERI team reported (http://www.eqclearinghouse.org/20100227-chile/general-information/observations-on-building-damage-from-francisco-medina) that the buildings were mainly reinforced concrete frame buildings, in contrast to the stiffer shear wall buildings used more commonly in Chile. The buildings housed the headquarters of many international companies, and the non-structural damage has forced closure of many of the buildings. Structural damage was mainly concentrated in areas around the openings (windows) and staircases (Figure 3-18, Figure 3-19 and Figure 3-20). The coupling elements between two parts of the wall on the sides of the openings were damaged with classic diagonal shear cracks (Figure 3-18 and Figure 3-19). Aside from the use of a more flexible lateral system, local media has suggested effects relating to the soil under Ciudad Empresarial, and possibly three-dimensional wave propagation effects related to the close proximity of the mountains as a reason for the severe damage experienced there (Personal communication: Juan Ferrer).

Figure 3-18: Damage to a hotel in Ciudad Empresarial, Santiago

Figure 3-19: Damage to the stair cases and surrounding area in a modern building in Ciudad Empresarial, Santiago (part of stair case has collapsed in the left and similarly the glassy facade on the other side of the building was broken with differential displacement at both sides)

Santiago airport suffered severe non-structural damage, including collapse of the suspended ceilings over much of the terminal buildings (see Figure 3-21). In the days following the earthquake, international flights were redirected to alternative airports, where passengers would go through customs and passport control and would then take a local flight to Santiago. At the time of the team's visit, the airport was fully operational, except for some of the shops and eateries in the terminals, although the suspended ceilings had not been repaired.

Figure 3-20: Damage to the structural system and facade of some modern buildings in Ciudad Empresarial, Santiago

Figure 3-21 Santiago airport – suspended ceiling collapse

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3.5 *Roads and Bridges*

3.5.1 Autopista Vespucio Norte Express

In Santiago damage was noted to several overpass bridges on the Autopista Vespucio Norte Express. The majority of the damage was only minor with many bridges showing some lateral movement at their bearings. However in the North West of Santiago (Figure 3-22) three sets of overpass bridges showed significant damage or had collapsed during the earthquake.

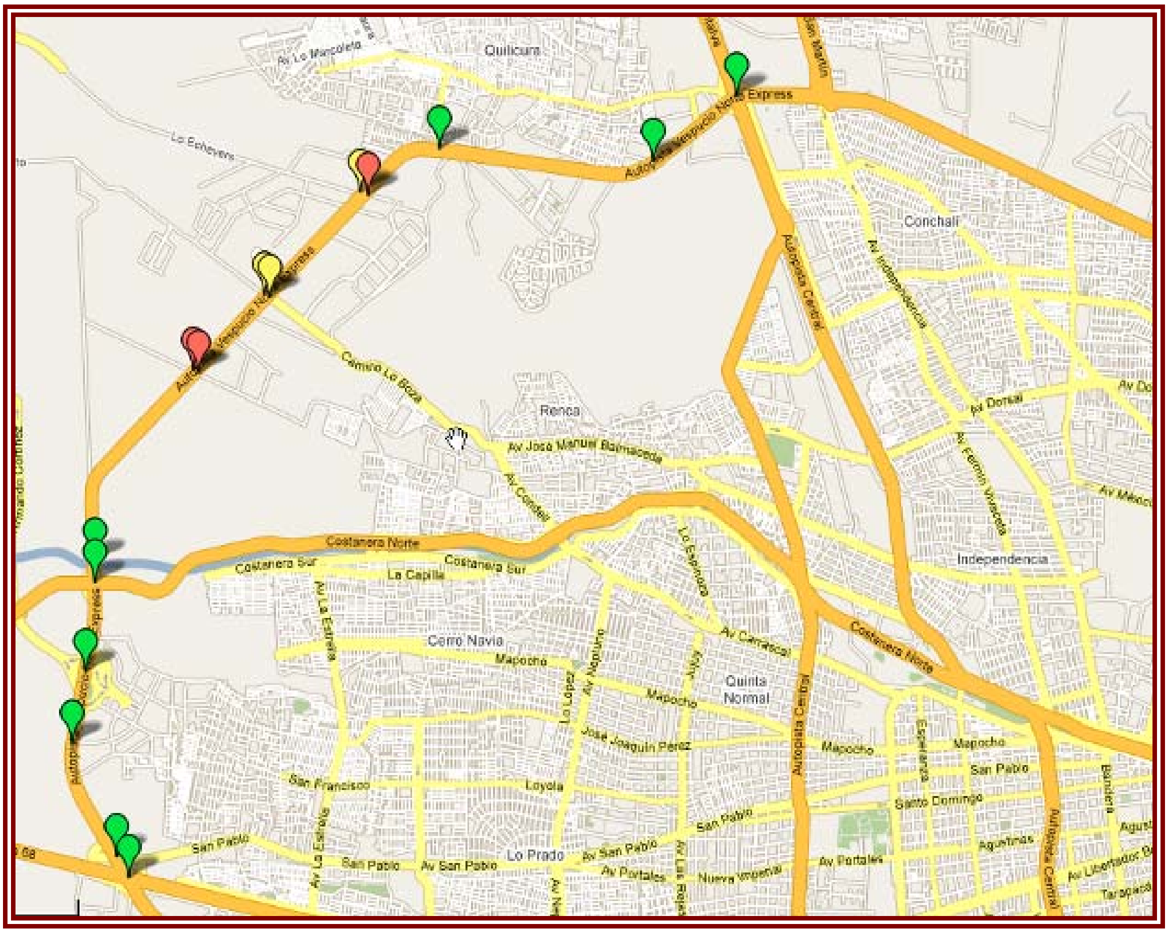

Figure 3-22: Bridge locations on the Autopista Vespucio Norte Express NW of Santiago. (Red – collapsed, Yellow - damaged, Green – not inspected in detail but no signs of major damage on drive past)

By the time the team arrived at the site of the southern most of the set of bridges, comprising two parallel 3 span skew bridges, the decks had been removed (Figure 3-23) leaving the abutments and two internal portal supports.

Figure 3-23: Remains of the southernmost set of overpass bridges.

Some minor cracking was noted at the bottom of the columns in the minor bending axis of the portals (Figure 3-24) but the main damage was at the top of the portals (Figure 3-25) where the steel brackets intended to provide vertical and lateral support to the deck beams had been pushed out of the concrete. Looking at those steel restraints that remained undamaged suggested that the deck beams had failed by rotating clockwise on plan and had subsequently fallen off their bearings.

Figure 3-24: Minor cracking at base of concrete columns

Figure 3-25: Damage to tops of support portals.

North of these bridges, the middle set of bridges (Figure 3-26) had not collapsed but showed significant damage to the restraint system. Unlike the southernmost set of bridges these were not skew bridges.

Figure 3-26: The middle set of overpass bridges.

It was clear that these bridges had also experienced significant lateral forces but, in this case, the forces were not high enough to unseat the deck beams. Many of the steel brackets restraining the bridge deck were bent (Figure 3.27) and several showed signs of shear failure of the concrete (Figure 3.28). As with the southernmost set of bridges those steel restraints that remained undamaged suggested that the deck beams had also rotated clockwise on plan.

Figure 3-27: Damage to deck restraints. Figure 3-28: Spalling of concrete around holding down bolts

At the northern most set of overpass bridges, again skew, (Figure 3.29) the eastern carriageway had collapsed while the western carriage way remained intact but badly damaged. Similar damage to the restraint system was observed (Figure 3.30) with the deck beams again rotating clockwise on plan.

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Figure 3-29: The northernmost set of overpass bridges. **Figure 3-30: Severe spalling of concrete at holding down bolts**

None of these bridges showed signs of foundation failure either at the internal supports or at the abutments but at all three sights there were obvious signs of high lateral forces on the bridge decks. Borehole data collected by Cruz et al. 1993 state that this area of Santiago has *"Alternating layers of low to medium plasticity silts and clays, interbedded with gravel layers. From the surface to about 9 m depth the deposits have a soft consistency, low relative density and SPT N value of 2-4. The S wave velocity is around 200 m/s from the surface to a depth of 10m. Below about 9m the strata have a firm to hard consistency and medium to very high relative density and the SPT N value is 35. The depth to water table is about 2 m, the depth to rock about 100 m"*. Cruz et al. 1993 also show that in this area the ground motions can be four times larger than at hard rock sites in Santiago. Therefore it is likely that amplification of ground motions due to the site conditions led to the damage to these particular bridges, with the skew bridges sustaining more damage than the normal bridges. The restraint system for the deck beams was also inadequate to carry the lateral forces to which it was subjected.

3.6 Ports

In terms of visits to port facilities in and around Santiago, the team did not get time to specifically visit any sites. The two major ports in the region are Valparaiso and San Antonio and the primary concern was clearly tsunami damage. A survey team from the Japan Society of Civil Engineers (JSCE) measured a run-up elevation of just over 5 metres above mean sea level in the form of dyke erosion and surveyed the region to the south of the main port, so there was clearly significant impact to coastal facilities.

However, San Antonio was the first location on the coast that was partially covered by the aerial overview flight courtesy of the Chilean Air Force. Several shots were taken of the southern coastal part of the town where debris from the tsunami could be clearly seen. The position of the run-up measurement recorded by the Japanese team is indicated in the photograph below.

As can be seen in Figure 3.32, which is the area to the top of Figure 3.31, the visible debris is of building material from similar structures to those seen in the foreground Figure 3.31. This is very severe damage and the previous grid layout can still be seen where the structures used to be. It would appear that the sea dyke protected the area to the north (Figure 3.31), but the unprotected area to the south (Figure 3.32) was completely lost to the tsunami.

Figure 3-31: Area protected by sea dyke structure

Figure 3-32: Area lost outside dyke

4 Region VI – O'Higgins

4.1 Background

The main cities and towns that were visited by EEFIT Region VI included Rancagua and San Fernando. A number of smaller villages were also visited including including Chepica, Lolol, Peralillo, Pumanque, and the valley of Cachapoal and Colchagua.

Figure 4-1 shows the itinerary of one of the EEFIT teams across the region. This team concentrated mainly on the damage to overpasses along the motorway Route 5. Figure 4.2 shows the itinerary of the other team which visited a number of small villages in the Valle de Colchagua, reach in settlers' heritage, from traditional fazendas, to vernacular casonas and churches.

Figure 4-1: O'Higgins Region

Rancagua – This is the capital of Region VI. It lies on the banks of the Rio Cachapoal and was founded in 1743. It has a population of 213,000.

San Fernando – This town lies on the Rio Tingirirca about 51km south of Rancagua. It is the capital of the Colchagua Province and is the market town for this fertile valley. It was founded in 1742, and became the provincial capital in 1840. It is the second most populated urban centre of the O'Higgins Region.

Chepica, Peralillo, Lolol and Pumanque – With more than 10.000 habitants, these little towns have most of their houses made of old adobe and confined masonry; cultural and historic heritage, 40% severely damaged by the earthquake including important historic churches and chapels.

Figure 4-2: O'Higgins Region with the itinerary followed along the heritage trail. In the map flags with letters indicate B, Peralillo, C, Pumanque, D, Lolol. Observation made in E, Lincanten and F, Curepto in the Septima region are discussed in the following chapter, although their observed intensity is included in table 4.1 for completeness.

4.2 Observed Intensities

Table 4-1 presents an estimate of the EMS intensity based on the observations, surveys and discussions with locals. More specific information about specific points of interest is provided in the following sections. In the tables the results for villages in both the O'Higgins and VII region are presented together as the building stock in these two areas is very homogeneous and provides a better understanding of the overall variation of intensity in the region.

Table 4-1: EMS intensity for O'Higgins Region

Town	Building Stock Observed†	Damage Observed‡	Intensity
Peralillo	**Many adobe building with or without quincha (confinement with timber (A-B)**	**Few collapsed**	**IX**
		Many structural damage to partial collapse	
	Few adobe buildings with confined masonry end walls (B) **Few Unreinforced masonry buildings (B)**	**Structural damage (3)**	
	Few confined masonry buildings (B-C)	**Light damage (2)**	
Pumanque	**Many adobe buildings in poor state of maintenance**	**Few total collapse (5)**	**VIII-IX**
		Many partial collapses (4)	
	Few adobe buildings well maintained	**Roof collapses (3-4)**	
		Structural cracks (3)	

Town	Building Stock Observed†	Damage Observed‡	Intensity
	Few unreinforced or confined masonry	**Light damage (2)**	
Lolol	**Many historic adobe buildings**	**Few partial collapse, many structural damage (3-4)**	**VIII**
	Few confined masonry	**Light damage (2)**	
	Very few concrete buildings	**None to structural damage (0,3)**	
Hualañé	Many adobe buildings (A)	Few collapsed (5)	VIII
		Many heavily damaged (4)	
	Timber hospital building (D)	Light damage (2)	
	Unreinforced masonry hospital building (C)	Light damage (2)	
Lincantén	Many adobe buildings (A)	Few collapsed (5) Many heavily damaged (4)	VIII
	Some confined masonry buildings (B-C)	Light to Structural Damage (2- 3)	
Curepto	**Many adobe buildings (A)**	**Many collapsed (5)**	**IX**

Locations in bold are covered in detail in separate subsections

- †EMS Vulnerability Class in parentheses
- ‡EMS Damage Class in parentheses
- *Difficult to separate damage due to tsunami and earthquake ground shaking; only latter included in EMS determination
- **With notable exceptions described in text

4.3 Historical and Vernacular Buildings

In Peralillo there are three major historic buildings, The church, almost 100 years old, the Casona y Parque, and the old school, listed as National Monument.. The Church was I adobe with timber columns encased in concrete to simulate Doric neoclassical columns, and un upper structure with vaut and roof in timber. The church had successfully survived the 1960 and the 1985 earthquake, but according to the technical Office of the Corporacion del Patrimonio de Colchaga the damage was to extensive to warrant restoration and it was completely demolished, without retaining not even the façade, which was in a very particular style. The Casona belonged to one of the oldest family in Peralillo, Echeñique Errázuriz, built by a French architect at the beginning of the 20th century, in mud, fired brick and and timber frame, set in a large parquet with a lake. The Casona, partially collapsed after the earthquake, was also demolished, while the Old Primary School built in the same style with timber framed brickwork, suffered modest damage and is being restored. Ford Chile is supporting the reconstruction effort in Peralillo.

The vernacular residential buildings in this region are mostly built in adobe and timber. Typically the walls are in adobe or quincha, or what is best known in this region as adobillo, a frame made of vertical and diagonal timber posts filled in with adobe blocks. In some cases the post are also connected with horizontal timber elements. Most buildings are one storey high and covered with two eaves roofs made of timber rafters resting on a ridge beam and on beam plates at the top of the adobe walls. The roof fabric is made of cane and mud covered with clay tiles. Very often the houses have a front porch shading the façade. The porches are made of timber elements connected with scarf joints and timber pins between posts and beams and between beams and rafter as it is visible from the pictures in Figure 4-5. In a minor number of cases the end walls are made of confined brick masonry. The rational for this is that, even if the adobe façade detaches and partially falls, the ridge beam will be supported by the more stable end walls, and hence roof collapse will be prevented. Broadly speaking, observation has confirmed that this arrangement works.

Figure 4-3: Peralillo, The Church, just after the earthquake and what was left after the bulldozers.

Figure 4-4: Peralillo, town house in adobe confined with wood columns (quincha) and the old school, with similar construction, which did not suffer any damage.

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Figure 4-5: Left: Peralillo Adobe house with porch. The scarf joints on the beams are visible over the columns; the porch is connected with horizontal struts to the adobe wall, hence providing some lateral restraint. The central column in the picture has shifted laterally from its support. Right: townhouse with confined masonry end walls. The adobe façade shows vertical cracks and the roof as partially caved in, but is still supported.

Pumanque is a small village of 3442 inhabitants, just south of Peralillo, initially settled in the 17th Century and is first mentioned in the bishopric documents in the XVIII century. A chapel was in existence in 1767, but the present church was erected in 1824. The original building was made of quincha (timber frame infilled with adobe) with a roof of straws and the floor of rammed earth. This building fell in disrepair and a new building was completed in 1870.This second building was destroyed by the earthquake of 1906 and the current one, with steel columns and timber walls and roof, was completed between 1910 and 1929 and retrofitted with concrete after the 1985 earthquake. As a result of the current earthquake only the retrofitted facade is left standing.

Figure 4-6: Pumanque: Nuova Senora del Rosario Church, before and after the earthquake. The green columns of the main nave are made of a steel profile with an outer concrete casting and the roof rests on a timber verendeel truss.

Figure 4-7: Pumanque: Adobe house confined with lightweight timber and damage to row of houses on main street.

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The two small villages of Lolol and Zuniga are considered to embody the historic criollo life of the end of the 19th century, The whole village of Lolol is listed as “zona tipica” and many of its buildings as national monuments due to the good state of conservation of both residential and public buildings, built in the traditional adobe and timber style with timber porches. The Consejo de Monumentos Nacionales (CMN) carried out an assessment in the area and concluded that 100 % of buildings had been damaged (personal communication, Monica Bahamondez, Chief Conservator). Specifically the district office counted 1175 houses as damaged and inhabitable, of these, 959 in rural areas and 216 in the urban centre, affecting 3475 people. During our survey we noted that many of the buildings had suffered some minor structural damage, such as vertical cracks and detachment among orthogonal walls, but had nonetheless been scheduled for demolition (see Figure 4-8**)**.

The parish of Lolol was established in 1824, while the current parish church was first erected in 1915 and consecrated in 1916. The church is built in adobe with a base in brickwork and fired bricks around the circular windows and around the two doors opening on each side wall. With respect to the original building, the bell tower was added in 1951, a wooden screen was added at the back of the façade, and the floor was tiled. The church suffered substantial damage in 1985 and was retrofitted with a thick shotcreting with wired mesh, both internally and externally but apparently without metal ties between the two. Failure seems to have been initiated around the openings at the interface between adobe and brickwork. The Council technical office is hopeful that the church can be restored.

Figure 4-8 Lolol: One of the listed houses on the main street. The graffiti in red on the left reads: “Patrimonio es nuestros ninos, no las casas” (heritage (but in this case also asset) are our children not our houses) and on the right in green “colapso total 100%” (total collapse).

Figure 4-9: The parish Church of Lolol: failure of the side walls around the lateral door, view of the internal structure of the nave in timber, Detail of the timber cladding above the arches, detail of the shotcreting of the external sidewalls introduced as repair after 1985 earthquake.

4.4 Roads and Bridges

4.4.1 Route 5

The route 5 expressway runs down much of the length of Chile. It forms part of the Pan American Highway and is the main transportation route up and down the country. Limitations on time and difficulties stopping on the expressway meant that it was not possible for the team to inspect all the bridges along route 5 from Santiago to Concepción (a journey of over 500km). However as the team travelled down this expressway a drive-by assessment was made of as many bridges as possible (Figure 4-10). From this map it is clear that throughout the area bridges had suffered some form of damage. Typically the problems were relatively minor, with excessive lateral movement at the abutments and compressive damage at the expansion joints being prevalent.

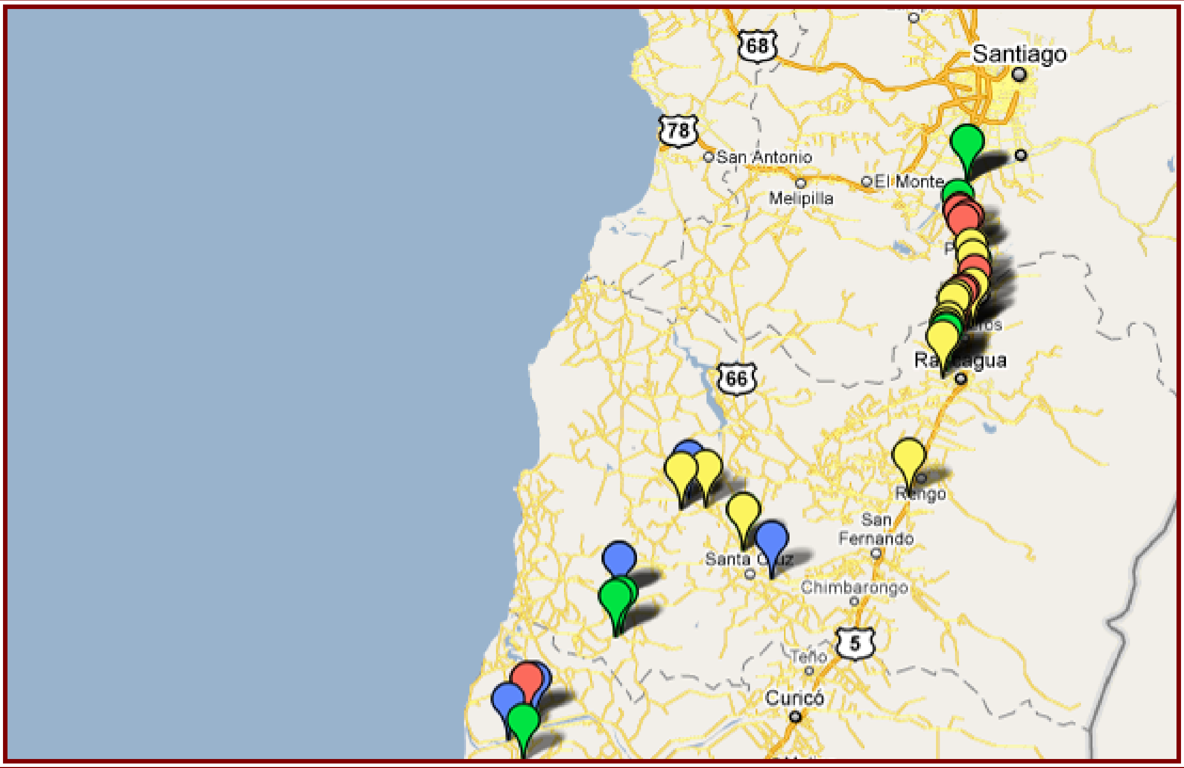

Figure 4-10: Bridge locations observed on the drive south. (Red – span(s) collapsed, Yellow - damaged, Green – appeared undamaged, Blue – severe settlement of road)

In most of these cases the bridges remained open. In some cases the damage was more severe, as shown by one bridge near Santiago (Figure 4-11). In this case the prestressed simply-supported concrete deck beams, had failed near both abutments. At the central carriageway support there was no damage to the beams although there was some lateral deck movement at the bearings. This bridge also shows the significant settlement of the soil adjacent to the abutment which was typical at many bridges along route 5. The abutments for this bridge were piled and although the tops of the piles were visible under the abutment, there was no sign of damage to the piles. A less severe example of lateral spreading and settlement of the approach embankments to a bridge can be seen in Figure 4-12 (left). Problems with settlement of the road surface occurred all along route 5 and in most places the dips had been filled with gravel by the time of the EEFIT mission so that the roads were passable. In some cases the settlement had also affected other road infrastructure such as the toll stations (Figure 4-12 right) and this may have been one reason that the tolls were not in operation during the teams visit.

Figure 4-11: Typical damage to overpass bridges near Santiago (left). Prestressing tendons can be seen in the detail on right (right).

Figure 4-12: Lateral spreading and settlement of bridge abutments occurred at many bridges (left). Road settlement at toll station (right).

Problems were also noted to many footbridges along the route travelled (Figure 4-13). In all the cases seen the spans affected were the approach spans, however it is probable that in cases where the main span had failed, the bridge had been removed by the time of the team's visit. Again the problems appeared to be bearing failures rather than structural failure of the deck. The majority of damaged bridges seen down route 5 were precast concrete bridges but there were a few exceptions. In a few places the predominantly steel bridges for the main railway line running close to route 5 were also badly damaged, however no failures of the steel were noted and most damage appeared to be at the bearings.

Figure 4-13: Typical footbridge failures

4.4.2 <u>Geotechnical Performance of Embankments</u>

The main road between Santiago and San Fernando had several detours mainly due to cracks in the pavement caused by either slope failure or lateral spreading. Some of the bridges suffered settlement and rotation; minor lateral spreading in the embankments was also observed (Figure 4-14 and Figure 4-15).

Figure 4-14: Crack in 5 Sur Road between Santiago and San Fernando City.

Figure 4-15: a) Bridge; b) Embankment along 5 Sur Road Santiago-San Fernando City

4.4.3 Country Roads

Where the team travelled off route 5 the same sorts of problems to the more minor bridges were noted. There were also many localised problems with settlement and lateral spreading of roads (Figure 4-16) near rivers and on embankments. However these types of slope failures were generally not apparent in natural slopes. One of the few examples of slope failures seen is shown in Figure 4-17 and like other failures it was very localized and of minor importance.

Figure 4-16: Typical damage to minor roads

Figure 4-17: Minor slope failure Main Road 5 Sur, between Santiago and Curico.

4.5 *Industry*

4.5.1 Wood Pulp Industry

The team observed a sulphur storage facility with significant damage just south of San Fernando on Route 5 (Figure 4-18). Sulphur is used by Chile's wood pulp industry (see Section 5.7.1) in the form of sodium sulphate in the conversion of the raw wood into cellulose fibres. It may also be used by the wine industry and as a fungicide by the produce industry.

Figure 4-18: Damage to sulphur storage facility south of San Fernando

The facility comprised single-storey confined masonry sheds, some of which experienced out-of-plane wall failures, presumably caused by the internal pressure of the sulphur. At the time of the team's visit, the sulphur was in a heap, having spilled out the sides of the storage building. Sulphur is not soluble in water, and is often stored in heaps with no protection from the elements; therefore the impact on this facility may not be great.

4.6 *Coastal*

On the whole, O'Higgins Region VI has few developed coastal locations. Much of the coastline is fairly rugged and sparsely populated. A few small towns exist usually associated with the mouths of estuaries. The largest of these towns is Pichilemu which appears from the aerial overview to have escaped serious tsunami damage. Some small settlements in low lying areas scattered along the coast have shown signs of structural damage and debris is visible from the air, but no major population centres were visibly damaged. Areas of land show visible signs of tsunami inundation by discoloured brown trees. This is caused by the saline intrusion and Figure 4-19 shows this clearly.

Figure 4-19: Saline intrusion from tsunami inundation, Northern O'Higgins Region

5 Region VII – Maule

5.1 Background

The main towns that were visited by EEFIT in Region VII were Curicó, Talca, Constitución, Cauquenes and the small resort of Pelluhue. Other towns and villages that were briefly examined included San Javier, Parral, Linares, Colbun, Hualane, Lincantén and Curepto.

Figure 5-1 shows the region, the areas visited by the EEFIT team. The following paragraphs provide a brief overview of the principal locations visited and their building stock.

Figure 5-1: Maule Region

Curicó – This town lies between the rivers of Lontue and Teno. Founded in 1743 it is the service centre for the region's vineyards. It has a population of 102,000.

Talca – Situated on the Rio Claro, a tributary of the Rio Maule, Talca lies about 56km south of Curicó. It is the most important city between Santiago and Concepción, with a population of 197,000. It is the major manufacturing centre and the capital of Region VII. Founded in 1692, it was destroyed by earthquakes in 1742 and 1928. The town is a mix of old abode and confined masonry houses and new reinforced concrete buildings ranging in height from 5 to more than 20 storeys. There are several industries in the vicinity of the town, which are related to the wine and soft fruit industries.

Constitución – This town, with a population of 38,000, lies about 89km west of Talca on the Pacific coast. It is situated on the southern side of the Rio Maule estuary. Founded in 1794 it is at the centre of the commercial logging area, which forms a significant portion of the local economy. A major wood pulp plant is situated on the coast. A twenty five span composite steel and concrete bridge crosses the river to the north. There is also a small fishing port, which services the local community.

Cauquenes – This market town lies between Route 5 and the coast and appears to support the local agriculture. A population of 31,000 resides in a mixture of adobe, lightweight timber and confined masonry houses of one storey. Around the town square there are number of two and three storey confined masonry structures which are in the Art Deco style, suggesting construction in the 1930s.

Pelluhue – This is a popular resort with the surfing community. The main square and many shops are situated on the higher ground of a headland to the south of the main beach. The principal building stock is of one and two storey lightweight timber frames, a few confined masonry houses and one reinforced concrete three storey building that houses the local boarding school. The buildings along the beach were predominately lightweight timber. A road runs approximately 150m parallel to the coastline and a two span precast concrete bridge crosses a small river.

Curepto – Small town first established in the year 1790. It is located in Maule Region, at 300 km southwest from Santiago. It's characterized by a Colonial architecture and mainly adobe constructions. The population is about 10.900.

5.2 Observed Intensities

Table 5-1 presents an estimate of the EMS intensity for the area based on observations, surveys and discussions with locals. More specific information about specific points of interest is provided in the following sections.

Table 5-1: Observed Intensities – Maule Region

Town	Building Stock Observed†	Damage Observed‡	Intensity
Hualañé	Many adobe buildings (A)	Few collapsed (5)	VIII
		Many heavily damaged (4)	
	Timber hospital building (D)	Light damage (2)	
	Unreinforced masonry hospital building (C)	Light damage (2)	
Lincantén	Many adobe buildings (A)	Few collapsed (5)	VIII
		Many heavily damaged (4)	
Curepto	Many adobe buildings (A)	Many collapsed (5)	IX
Talca	**Many adobe buildings (A)**	**Few collapsed (5)**	**VIII**
		Many heavily damaged (4)	
	Some confined masonry buildings (D)	**Light damage (2)**	
	Some RC shear wall buildings (E)	**Minor damage (1)****	
Constitución*	**Many adobe buildings (A)**	**Many collapsed (5)**	**IX**
	Some confined masonry buildings (D)	**Some moderately damaged (3)**	
		Some lightly damaged (2)	
	Few RC shear wall buildings	**Some undamaged (0)**	
		Some minor damage (1)	
	RC moment frame 1-storey house	**Minor damage (1)**	
San Javier	Few adobe buildings (A)	Many heavily damaged (4)	VIII
	Lightweight steel framed supermarket building (E)	None (0) or minor damage (1)	
Cauquenes	**Many residential adobe buildings (A)**	**Some collapsed (5)**	**IX**
		Many heavily damaged (4)	
	Confined masonry cinema and bank (D)	**Moderately damaged (3)**	
	RC shear wall school building (E)	**Moderately damaged (3)**	
	RC shear wall and steel commercial buildings (E)	**Some minor (1) and light (2) damage**	
Pelluhue*	**Very few adobe buildings (A)**	**Not observed**	**VIII**
	Many confined masonry buildings (D)	**Minor damage (1)**	
	RC shear wall boarding school (E)	**Light damage (2)**	
Parral	Many confined masonry buildings (D)	Some minor (1) and light (2) damage	VII
	Concrete silo	One failure	
Linares	Many confined masonry buildings (D)	Some minor (1) and light (2) damage	VII
Colbún	Some adobe buildings	Some minor damage (1)	VI

Locations in bold are covered in detail in separate subsections

Town	Building Stock Observed†	Damage Observed‡	Intensity

- †EMS Vulnerability Class in parentheses
- ‡EMS Damage Class in parentheses
- *Difficult to separate damage due to tsunami and earthquake ground shaking; only latter included in EMS determination
- **With notable exceptions described in text

5.3 Historical and Vernacular Buildings

An overview of the effect of the earthquake on the heritage buildings in the Maule region is provided in Table 5.2 divided by historical monuments or zonas tipicas (conservation areas) *(source Monumento del Maule),*

http://www.monumentosdelmaule.cl/Terremoto%202010/Catastro%20Region%20Maule.pdf .

Table 5.2: State of damage of national monuments and zonatipicas in the Maule region by province

				Damage state		
Location	Categoría	Total number	Surveyed	**Grave (G)**	**Regular (R)**	**Bueno (B)**
Provincia de Talca	MH	13	13	7	3	3
Provincia de Curicó	MH	5	5	3	1	1
Provincia de Linares	MH	7	7	2	2	3
Provincia de Cauquenes	MH	1	1	1	-	-
Puentes	MH	6	6	1	-	5
Ramal Talca-Constitución	MH	1	1	1	-	-
Total		**33**	**33**	**15**	**6**	**12**
Provincia de Talca	ZT	1	1	1	-	-
Provincia de Curicó	ZT	2	2	2	-	-
Provincia de Linares	ZT	4	4	2	1	1
Provincia de Cauquenes	ZT	1	1	1	-	-
Total		**8**	**8**	**6**	**1**	**1**
Total Monumentos Nacionales Inmuebles		**41**	**41**	**21**	**7**	**13**

In Talca severe damage was recorded on many adobe buildings, and some of the early 20th century buildings around the Plaza Mayor, although for these the damage was structural but without collapses. An exception is constituted by the Central Market buildings. These had been already abandoned and were in disrepair, with various studies already proposed for their rehabilitation and change of use. However part of the end walls collapsed and currently what is left is threaten with demolition.

The main church in Talca is built in confined masonry and although it sustained a few cracks, the damage is essentially moderate.

Figure 5-2: Central markets in Talca

Figure 5-3: Left: example of hammering between to masonry buildings in Plaza mayor and right, Cathedral of Talca

The centre of Curepto is also a Zona tipica, since 1990, and it is estimated that 50% of the houses have been severely damaged. Curepto was initially settled around the mid 17th Century, while a parish was established here in 1783. The parish church of Curepto, Nuestra Señora del Rosario, was first built in 1835, by the whole community during 10 years. The church was damaged in 1985 and substantially retrofitted including cross ties and a tick shotcreting plaster poorly reinforced. The walls with the cross ties resisted the shocks but where there were no ties the shotcreted layer exploded and the internal adobe wall collapsed.

Figure 5-4: The parish Church in Curepto: loss of the façade plaster and partial collapse of the south nave. The anchoring system is visible in façade at the ceiling level.

5.4 Modern Buildings

The team visited some modern buildings in some of the bigger towns in the region, Talca, Cauquenes and Constitución. As with other areas affected by the earthquake, mid-rise and high-rise buildings were predominantly reinforced concrete shear wall buildings, whilst a few low-rise reinforced concrete moment frames and lightweight steel frame buildings were also observed. For the most part, modern construction performed well, and significant damage or failures could usually be attributed to architectural features or design flaws in the buildings. No shear wall longitudinal reinforcement buckling was observed in Maule (in contrast to failures seen in or around Santiago; see Section 3.4).

5.4.1 Talca

Two reasonably typical multi-storey apartment buildings from Talca are shown in Figure 5-5, both of which were essentially undamaged. The team could find no indications of any damage in the 13-storey Edificio Costa Azul (left; opened 2008), aside from some superficial cracks in internal partitions which had already been repaired at the time of visit. There was no observable cracking in beams and shear walls on the ground level or basement level. A 22-storey apartment building on Av O'Higgins (right) also seemed to be unscathed, although the team were not able to visit the interior.

Figure 5-5: Typical undamaged apartment buildings in Talca: Edificio Costa Azul (left) and new building under construction on Av O'Higgins (right).

The 8-storey Hotel Diego de Almagro building, where the team was based in Talca, was lightly damaged, with cracking in façade panels above windows at the 2nd and 3rd floors (Figure 5-6), and internal cracking to partitions.

Figure 5-6: Hotel Diego de Almagro and light damage above windows on 2nd and 3rd floors

The team observed more damage in the 18-storey Edificio Amalfi (Figure 5-7, left; opened 2008), located in central Talca, although there was nothing to indicate that the damage would not be repairable. The building was L-shaped in plan, with movement joints between the two legs of the L to allow independent movement. The two legs were connected non-structurally, which led to both internal and external cracking at the interface to façades and finishes (Figure 5-7, middle). There was also damage to façade tiles at some locations (Figure 5-7, right).

A notable feature in the Edificio Amalfi was the heavy spalling damage to lintel beams above doorways in almost every apartment in the building (Figure 5-8). From structural drawings, the lintels were typically 475 mm × 200 mm deep with 0.25% conventional (horizontal) reinforcement top and bottom – this relatively light reinforcement could explain the heavy damage observed. It is not clear if the lintel beams were intended to act as primary beams, coupling the shear walls, but it appears that they were merely architectural with minimal reinforcement. Nevertheless, the links at 150 mm spacing appear to have successfully confined the core concrete, and only spalling of cover concrete was observed.

The building administrator of the Edificio Amalfi reported that there had been flooding in the basement following the earthquake, and subsequently property stored in the storage rooms in the basement was damaged. He also told the team that, as of March 2010, only 40 out of 250 units had been reoccupied, due to residents' concerns about the earthquake damage, and the perceived risk of aftershocks.

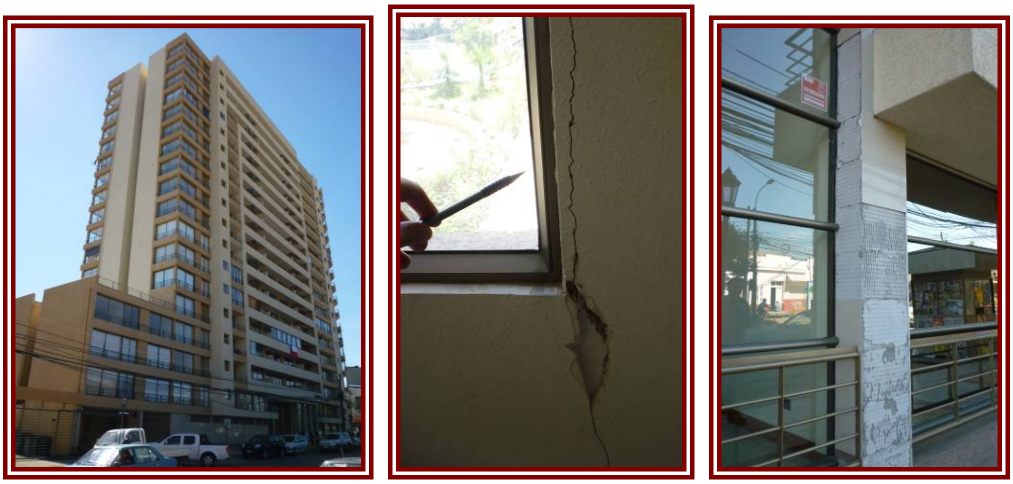

Figure 5-7: Edificio Amalfi, damage to finishes at movement joint in building, and damage to façade tiles.

Figure 5-8: Edificio Amalfi – Heavy spalling of door lintels but core concrete intact.

A less successfully performing building was the 5-storey Edificio Aranjuez building in central Talca (Figure 5-9, left), one of two modern buildings in Talca that the team would classify as not having satisfied the “life safety” performance objective of the Chilean code. The lateral system comprised reinforced concrete shear walls, which had failed in out-of-plane bending in the upper level. It appeared that the walls were insufficiently tied to the roof diaphragm to resist out-of-plane loads. A close-up inspection of some of the rubble from the failure (Figure 5-9, right) suggested that small longitudinal reinforcing bars – of the order of 6 mm – were used in the wall, and that no or limited transverse reinforcement was provided.

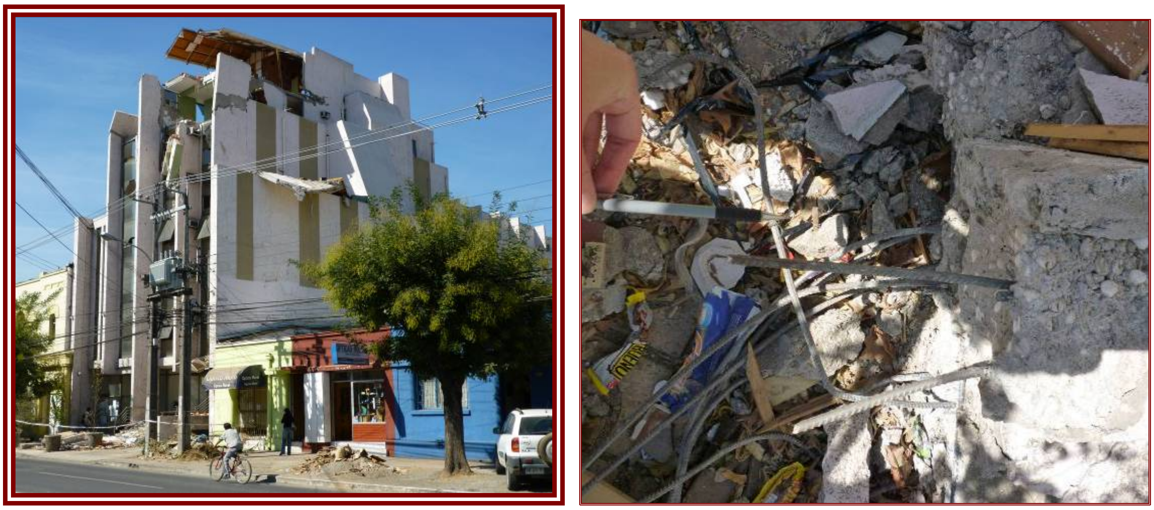

Figure 5-9: Edificio Aranjuez: out-of-plane failure of walls and reinforcement in rubble

The other modern building in Talca that did not achieve life safe performance was the Court of Appeals building on Av O’Higgins. The building was a reinforced concrete shear wall building, L-shaped in plan but with a triangular section attached to one of the legs of the L (Figure 5-10, left). Apart from some damage to glass panels between shear walls (Figure 5-10, middle), there did not appear to be significant damage to the main L-shaped body of the structure. However, a large beam along the top of the triangular section had completely unseated, smashing into the structure below, and was left dangling from limited reinforcement at the time of the team’s visit (Figure 5-10, right). There appeared to be little or no reinforcement connecting the two beams, and they were seated on a very small “column” supporting their weight but providing insignificant resistance to their inertia. The team’s impression was that the detail was purely architectural, and yet could have compromised the “life safe” performance of the building had the earthquake occurred at a time when it was occupied.

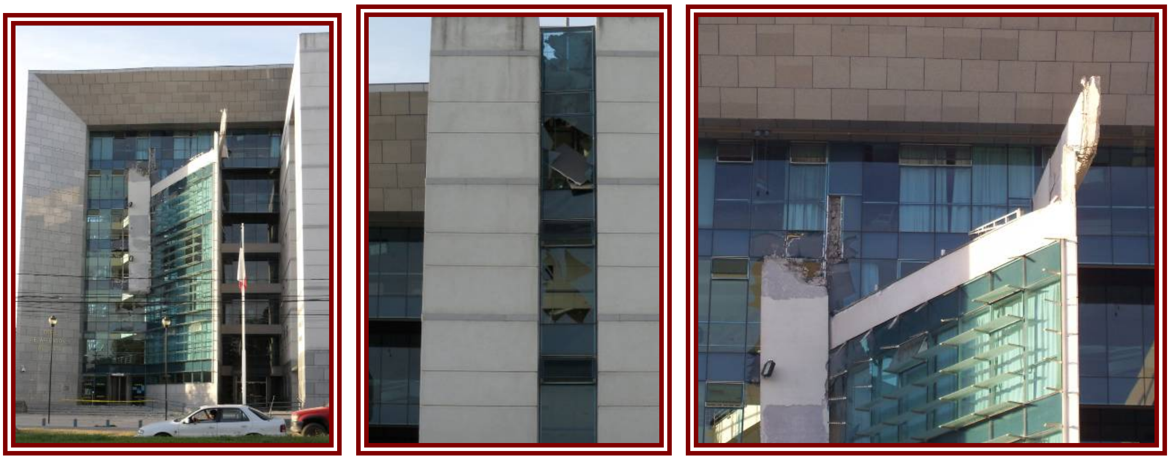

Figure 5-10: Talca Court of Appeals building

5.4.2 Constitución

Outside of Talca, the team visited some modern low- to mid-rise buildings in the tsunami-affected Constitución and Pelluhue. Two identical five-storey apartment buildings (one shown in Figure 5-11, left) experienced very little structural damage, despite wave heights above the ground level (evidenced by broken windows on the ground and first floors), and scour of up to 300 mm at the foundations (Figure 5-11, right).

Figure 5-11: Apartment building near waterfront in Constitución and scour at foundations

Another successfully performing modern building was a two-storey house on O'Higgins – the third street back from the river in Constitución (Figure 5-12). The building had a reinforced concrete frame in the ground storey, with timber infills, and a timber frame / timber infill first storey. The only visible damage was a cracked façade tile that covered the concrete frame at the base of the column. The owners of the building were very interested in explaining to the team the level of engineering that had gone into the construction, and its subsequent successful performance, in contrast to most other buildings in this area of Constitución. The pride that the owners felt for a non-traditional building solution was an interesting lesson to draw from the team's visit, and could be contrasted with the desire for "culturally-appropriate technologies" common to post-disaster reconstruction.

Figure 5-12: RC frame building with timber infills and practically no damage

5.5 Emergency Buildings

5.5.1 Hospital in Talca,

The hospital and clinics in Talca are spread over several buildings, constructed between 1937 and 2007. Through media reports (e.g. http://news.bbc.co.uk/1/hi/world/americas/8546121.stm) and local testimony, the team were told that the hospital had suffered severe damage in the earthquake, and that this had affected the operability of the hospital for dealing with casualties of the event. At the time of the team's visit, the main hospital operations were understood to have been moved to the specialist Centro de Diagnostico Terapeutico building, constructed in 2007, as the older buildings were unusable. The team was not able to enter any of the hospital buildings.

One of the more modern buildings, a clinic, lost a parapet along its front façade, and sustained minor damage to façade cladding (Figure 5-13, left). There did not appear to be any damage to the lower levels. There was apparent damage to older confined masonry buildings (Figure 5-13, right), but it was difficult to determine the extent of damage from outside the hospital compound. There was no discernable damage to the Centro de Diagnostico Terapeutico building (Figure 5-14).

Figure 5-13: Damage to hospital buildings in Talca

Figure 5-14: Damage to old hospital building and no discernable damage to modern hospital building in Talca

5.5.2 Hospital in Constitución

The hospital in Constitución appeared to have sustained only minor damage, notwithstanding the pile of rubble on the footpath outside which suggested more internal damage (Figure 5-15). According to hospital workers, it was operational immediately following the earthquake. The hospital, located at the south-east end of the city centre, appeared to have been above the height of the tsunami.

Figure 5-15: Minor damage to hospital building in Constitución

5.5.3 Fire Station, Constitución

The masonry fire station in Constitución was heavily damaged by the earthquake and tsunami (Figure 5-16), and was not in operation at the time of the team's visit. Damage included the collapse of a belltower and parapets around the roof of the station, and severe damage to external walls.

Figure 5-16: Severe damage to fire station in Constitución including collapsed tower and parapet, and damage to external walls

5.6 Roads and Bridges

Figure 5-17: Bridge locations observed on the drive south. (Red – span(s) collapsed, Yellow - damaged, Green – appeared undamaged, Blue – severe settlement of road)

5.6.1 Rio Mataquito Suspension Bridge, Lincantén

This footbridge was located at the west side of town on the road to Curepto at a local panoramic outlook. The bridge was constructed with steel towers made from tubular sections and a steel deck. There was no sign of damage except for the collapse of the southern approach span as shown in Figure 5-18.

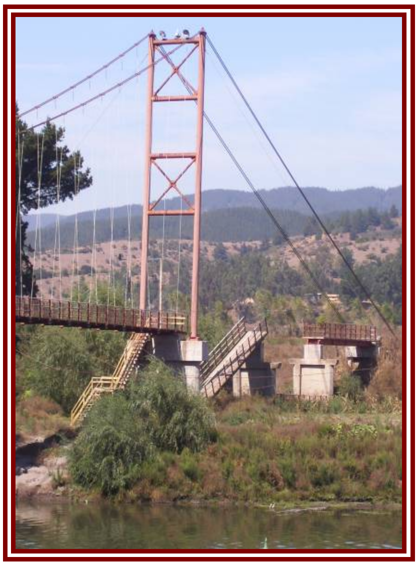

Figure 5-18: Suspension bridge failure, Lincantén

5.6.2 Rio Claro Bridge, Curicó

The Rio Claro river, south of Curicó was crossed by two bridges for Route 5 – a 200-year old masonry arch bridge carrying southbound traffic, and a more modern concrete arch bridge carrying northbound traffic. The older bridge collapsed in the earthquake (Figure 5-19). Much of the debris had been cleared away by the time the team arrived, with just a central masonry pillar supporting a section of roadway remaining. Southbound traffic was rerouted onto the northbound bridge, showing the benefit of redundancy that having separate bridges for each carriageway allows.

Figure 5-19: Rio Claro Bridge (southbound traffic) collapse

The northbound bridge (Figure 5-20, left) showed no discernable damage, except shear failure of the transverse shear key closest to mid-span (Figure 5-20, centre). Other shear keys did not appear to be damaged. Interestingly, there was evidence of either repair (following previous earthquakes) or retrofit at the end of the bridge, where ~250 mm thick panels of concrete had been cast between girders (Figure 5-20, right).

Figure 5-20: Rio Claro Bridge (northbound traffic), shear failure of transverse shear key at midspan, and evidence of retrofit or repair from previous earthquakes

5.6.3 Cardenal Raul Silva Henriquez Bridge, Constitución

The Cardenal Raul Silva Henriquez Bridge on the M-24-K road leading out of Constitución to the north-west was visited by the team, and was operational at the time of the visit. The bridge has 24 spans, with central piers supported by an island in the middle of the river, and is located approximately 3–4km from the mouth of the river. It would have been in the direct path of the tsunami.

The bridge is of composite construction – spans at the north-east end are supported on 2 or 3 circular concrete piers, connected by a concrete pier cap (Figure 5-21 left); spans at the south-west end are supported on raked steel piers and a steel pier cap (Figure 5-21 centre). The steel piers were presumably required to support the taller spans at the south-west end. Some of the concrete piers showed signs of light cracking (~1mm) due to transverse movement, on both the upstream and downstream sides (Figure 5-21 right). The concrete bridge deck was supported on steel I-girders.

Figure 5-21: Cardenal Raul Silva Henriquez Bridge, Constitución. Concrete piers at north-east end, and raked steel piers at south-west end. Light cracking to concrete piers.

Aside from the light concrete cracking, the bridge had undergone significant lateral movement, and steel transverse shear keys on both sides were almost completely flattened in some locations (Figure 5-22, left and centre). Of more concern, there was significant residual transverse displacement – around 300mm at mid-span – of the deck towards the upstream side. It seems that the bridge was fortunate to survive the earthquake without unseating, and that the deck will need to be jacked back into position before the next major earthquake occurs.

There was also evidence of buckling of steel members used for lateral bracing of the steel girders, presumably due to lengthening under tensile yielding, followed by buckling in the compression cycle (Figure 5-22, centre and right). The buckling was mostly evident in the upstream side, consistent with the residual displacement of the bridge being towards the upstream.

Figure 5-22: Cardenal Raul Silva Henriquez Bridge, Constitución. Displaced shear keys and significant residual lateral displacement, residual displacement along bridge and buckling of girder lateral bracing.

A small road leading down to the river on the north-east side of the bridge showed large cracks (> 100mm) due to lateral spreading.

Figure 5-23: Significant lateral spreading of soil and damage to roadway close to Cardenal Raul Silva Henriquez Bridge, Constitución.

5.6.4 Bridge on M-80-N, Pelluhue

A two-span concrete bridge on the M-80-N road to the north of Pelluhue (Figure 5-24) was operational and not severely damaged, except for the steel railing, despite its location near the mouth of the river and in the direct path of the tsunami. The transverse shear key on the upstream side of the bridge showed significant spalling (Figure 5-24), while the shear key on the downstream side showed no discernable damage, suggesting that the damage was caused by the incoming tsunami wave rather than ground shaking.

Figure 5-24: Bridge on M-80-N in Pelluhue, and damage to shear key on upstream side.

5.7 Dams

Before the mission ICOLD were contacted to identify whether there were any significant damage to dams. We were informed that since the earthquake occurred towards the end of the dry season when reservoir levels are low, no un-managed water releases were reported and damage was limited. Minor damage was reported at three water storage dams: Lliu Lliu, Huelehueico and Coihueco. One failure of tailings dam (old mine workings) suffered significant lateral spreading, with reported displacements of more than 700m.

Since damage to the main water storage reservoirs was limited and due to logistical constraints only two dams were visited. The first was the San Esteban reservoir, which is shown in Figure 5-25. This is an embankment dam reservoir. The pictures show the low level of the reservoir, but despite this some minor longitudinal cracking was observed along the crest to the north side of the sluice gate.

Figure 5-25: San Estaban Reservoir

Figure 5-26 shows the upper Colbun Dam and the main channel leading from the Lower dam. Clearly the water level was very low. No damage was observed to the main embankment dams during our brief inspection. However, it is understood that one of the levees (away from the dam) collapsed two days after the largest of the aftershocks on the 11th May 2010. The exact reason for the failure is unclear (GEER, 2010).

Figure 5-26**: Colbun Dam**

5.8 Coastal

Several areas in Maule were severely affected by the tsunami. Small towns along much of the coast were inundated by tsunami of several metres above mean sea level and parts of the region experienced some of the highest recorded run-up data from the other international survey teams. For this reason, areas of Maule showed some of the worst tsunami damage seen on the mission. To the north of the region around Iloca several small coastal villages were heavily damaged by tsunami, as shown in Figure 5-27. This was the story for much of the Maule coastline as seen from the air. Similar levels of damage were observed from the flyover in Pelluhue, Curanipe, and other smaller settlements along the coast. Run-up heights in Pelluhue and Curanipe measured by the JSCE team were 6.1 and 7.3 metres respectively.

Figure 5-27: Severe damage to villages around Iloca

Though the damage to the smaller villages was severe, Constitución appears to have fared badly. The JSCE team measured their largest run-up values here on a hill south of the paper mill around 27 metres (top, centre of figure 5-28). These run-up values are extremely high, but are also very localised. Run-up in Constitución itself was generally between 5 and 11 metres.

As part of the Earthquake Engineering Field Investigation Team (EEFIT) post-earthquake survey, a one-day survey was carried out looking at the downtown area of Constitución, the Cardenal Raul Silva Henriquez Bridge on the M-24-K road leading north-west and the Arauco plant on the Pacific coast.

This survey indicated extensive damage to the city along the south bank of Rio Maule. High water marks were noted on several buildings that indicate a minimum tsunami flow depths above ground level were between 4 to 5m close to the river, reducing to about 1.5 to 2m further inland.

Extensive damage to structures in the inundation zone was visible from the air and from the ground the effects of scour could be clearly seen. The first two streets from the shoreline were almost totally destroyed, where the structures had been subjected to the most severe effects of the waves close to the river.

Figure 5-28: Aerial shot of Constitución looking south across the Rio Maule

Following the streets further inland from the river, the damage was less severe, but still apparent on many structures in an area that followed the outline of inundation maps made by SHOA (Figure 5-29) reasonably well. This inundation model was based on the Mw8.2 1835 event and had been publicised over the last few years as part of a wider hazard assessment programme for the region.

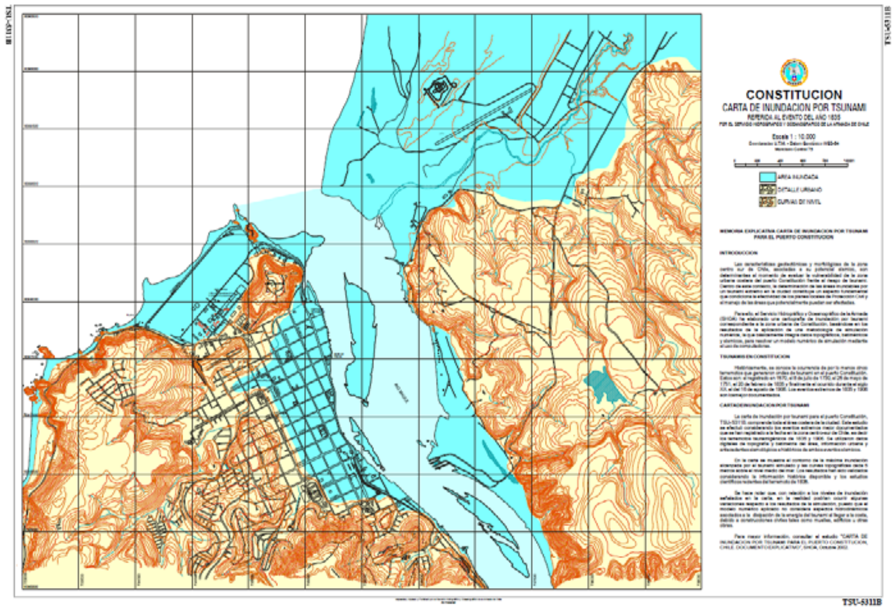

Figure 5-29 - Inundation map of Constitución by SHOA

Information on the tsunami impacts at Constitución and tsunami run-up estimates, including high resolution inundation maps have been compiled by Armijo et al. (2010). The limit of inundation has been added to the aerial photograph shown in Figure 5-30. This shows the 2010 inundation (dark blue) closely resembles, though is slightly less severe than the pattern of the 1835 tsunami (light blue).

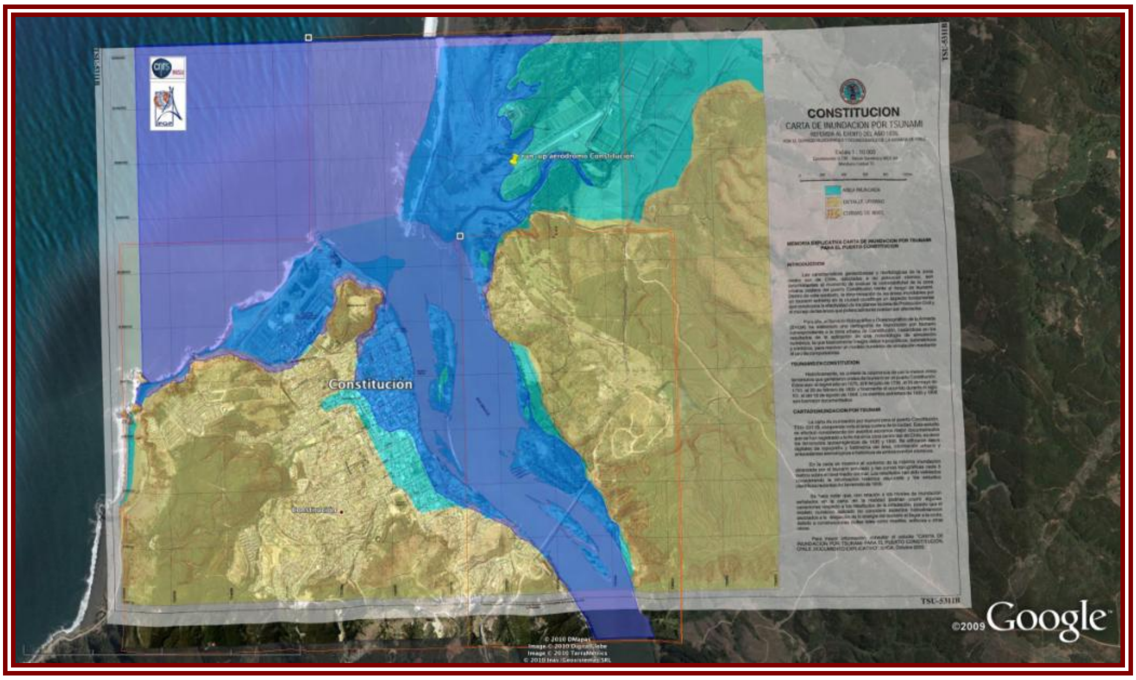

Figure 5-30 Overlay of 2010 inundation and SHOA Inundation map using Google Imagery, Armijo et al. (2010)

Away from the river the terain rises slowly until the gradient increases into the hills. The tsunami inundation followed this topography and evacuation routes present in the town capitalise on this natural high ground by directing people towards this safe area. From this perspective Constitución is lucky to be in proximity to such safe areas and future mitigation plans are likely to utilise this natural tsunami refuge.

Figure 5-31: Evacuation route sign Constitución

Figure 5-32: Seawall in front of the Auraco plant, before and after tsunami

The region to the north west of the town, directly on the Pacific coast is occupied by a wood pulping plant owned and run by Aurauco and this was fairly badly affected by the tsunami.

Figure 5-32 (a) and (b) show before and after photographs of the sea-wall, comprising large reinforced concrete blocks and an embankment, along the coast infront of the Arauco plan.

EEFIT

6 Region VIII – Biobío

6.1 Background

The main cities and towns that were visited by EEFIT in Bio-Bio were Chillan, Concepción and Talcahuano. A number of other coastal towns were also visited which are shown on Figure 6-1. The following paragraphs provide a brief overview of each location and their building stock.

Figure 6-1: Bio-Bio Region

Chillan – Located 150km south of Talca, this city has relocated several times. It was originally founded in 1580, destroyed by the Mapuche Indians and more recently by the 1833 earthquake.

Concepción – The capital of Region VIII, Concepción is the third biggest city in Chile, with a population of about 250,000. Founded in 1550, it was destroyed by an earthquake in 1751 and moved to its present site in 1764, but suffered another destructive earthquake and tsunami in 1835. It is one of the Chile's major industrial centres. It is sited just inland of the port of Talcahuano, which houses Chile's most important naval base.

Talcahuano – Situated on the Peninsula de Tumbes, this town provides the best harbour in Chile, is the main naval port and an important commercial and fishing port. Many important industries such as shipbuilding and ship repair Company ASMAR S.A. and Iron production Company Huachipato S.A. are the major economic sources of this city. The population is about 250,348.

Penco – It is located in the original place were the city of Concepción was founded, but the earthquake and tsunami of 1751 destroyed this city and the authorities prohibited the construction in this area, until the year 1840 when the city of Penco was founded. This city is unified with Lirquen, an important port, and together they have a population of about 41,000.

Tome – Located at 39 km from Concepción, it was founded in the year 1850. The economy was mainly driven by the fabric wool industry and fishing; both of these economic sources have closed, giving this city one of the highest unemployed rates in the country.

Coliumo – Small fishing port and touristic area, 8 km north of Tome.

Dichato – Northeast of the city of Concepción, it is an important touristic beach and small fishing port with 4384 habitants.

6.2 Observed Intensities

Table 6-1 presents an estimate of the EMS intensity for the area based on observations, surveys and discussions with locals. More specific information about specific points of interest is provided in the following sections.

Table 6-1: Observed Intensities Bio-Bio Region

City/town	Distance from the epicentre (km)	Region	Population	EMS
Talcahuano	137	VIII Bio-Bio	250.348	9
Concepción	115	VIII Bio-Bio	666.381	9
Chillan	100	VIII Bio-Bio	162.000	8
Penco	101	VIII Bio-Bio	41.000	9
Tome – Coliumo - Dichato	100 (average)	VIII Bio-Bio	52.440	9

6.3 Street survey to assess extent of damage to building stock

While in Concepción the team was able to spend some time doing a visual survey of a set of 9 city blocks. The area covered (in the south west of the city) included a variety of different construction types, including unconfined masonry, confined masonry and RC structures. The 382 buildings surveyed were predominantly 2 storey residential properties intermixed with a few high rise apartments, light industrial buildings and small shops. From geotechnical maps (Figure 7-2) the ground conditions throughout the area surveyed are classified as silty sand. Every building was photographed and from these pictures the level of damage to each structure was assessed with damage being classed as Superficial damage (class 1), Moderate Damage (class 2), Substantial or Very Heavy damage (classes 3 & 4). Examples of these damage levels are shown in Figure 6-2. Where there were piles of rubble outside a building, but no obvious damage to the structure (Figure 6-3), this was also noted. It was apparent from the walk around the area that in the weeks between the earthquake and the team's mission a significant clear up had taken place in Concepción. It is therefore likely that many more structures were damaged internally, but by the time of the mission no clear indication that there had been internal damage remained.

Figure 6-2: Examples of damage assessment from photos: (left to right) Superficial damage, Moderate Damage, Substantial to Very heavy damage

Figure 6-3: Example of rubble left outside a property indicating some level of damage internally but no obvious external damage

Figure 6-4: Block survey showing locations of damaged structures: Superficial damage (Yellow), Moderate Damage (Orange), Substantial or Very heavy damage (Red), Rubble on street (Blue).

Figure 6-4 shows a map of all the damage noted in the 9 block survey area. A total of 34 buildings were assessed as showing superficial damage (Yellow), 20 showing moderate damage (Orange), 10 showing substantial or very heavy damage (Red) and a further 10 buildings had rubble on street in front of the building (Blue). Therefore of the 382 buildings surveyed 30 (8%) had obvious structural damage). No very clear patterns of damage emerge but there does appear to be a concentration of very badly damaged structures in the southern part of this area. In this area many of the buildings appeared to be older with the unconfined masonry buildings amongst them performing least well.

6.4 Modern Buildings

In the Bio-Bio region the team concentrated its efforts in the main city of Concepción and visited a number of the modern buildings in this city that were damaged. Concepción was situated just 115km from the epicentre and in addition to the main earthquake event had experienced many large aftershocks. As with the other areas affected by the earthquake, the mid-rise and high-rise buildings were predominantly reinforced concrete shear wall buildings. A few low-rise reinforced concrete moment frames and lightweight steel frame buildings were also observed. Generally modern construction performed well, but there were some significant high profile failures in very recently constructed buildings, many of these being no more than 5 years old. These buildings in particular are described below. In general the damage to modern buildings could be attributed to architectural features or design flaws in the buildings but in several cases there is also the possibility that poor construction led to the failure of the buildings.

6.4.1 Modern Buildings in Concepción

Before the team left the UK the team obtained a list of the major buildings in Concepción that had been identified by the City Council of Concepción as having two different levels of damage. Category 1 structures were defined as ‘buildings that were likely to collapse in small earthquakes and therefore have to be demolished’. Category 2 structures were defined as ‘buildings that had severe damage to their structures and therefore might collapse in stronger earthquakes so have to be studied in more detail to see if it is possible to repair them or whether demolition is necessary’. In Concepción a total of 8 buildings in Category 1 had been defined and a further 67 in Category 2. The team made an effort to visit as many of these buildings as possible to assess the levels and types of damage and the buildings on this list visited by the team are shown in bold in the table below. It is worth noting that this list, with only a few exceptions, didn’t include any of the buildings with less than 3 storeys or other non-residential buildings. In addition to the buildings listed in Table 6-2 the team saw a great many other buildings were also badly damaged. Nevertheless the list was very useful in identifying many of the larger structures that had extensive damage.

Table 6-2: List of badly damaged modern building in Concepción. Those underlined are discussed in more detail below.

Category 1	**Category 2**	**Category 2**	**Category 2**
<u>Caupolican 518</u>	Andres Bello 172	**<u>Colo-Colo 1372</u>**	O'Higgins 465
Los Carreras 1535	Angol 445 - Templo Adventista	Colo-Colo 379	O'Higgins 495
Salas 1343	Angol 599	Costanera Andalien sur 221	**O'Higgins & Anibal Pinto Banco Edward City**
<u>Torre O’Higgins 241</u>	**Anibal Pinto 685**	**Desiderio Sanhueza 659**	O'Higgins & Caupolican
<u>Lincoyan 440</u>	**Anibal Pinto 817**	Edificio Intendencia - Sector Estacion	Orompello 476-472-470-466
Freire 1165	Barros Arana 1037	Facultad de Odontologia - UDEC	**Orompello 555-559**
Rozas 1145	Barros Arana 130	**Freire 1032**	Pedro de Valdivia 1653
Padre Hurtado	Barros Arana 165	Freire 348	Prat 434
	Barros Arana 289	Freire 40	Prat 454

Barros Arana 298	Freire 82 / 76	Prat-Plaza España Hotel Cecil
Barros Arana 741	Geswein 70	Rengo 635
Barros Arana 780-790	San Martín & Lincoyán Iglesia Santo Domingo – figure 1	Rengo 659-669 - Residencial Central
Barros Arana 979 983 last level	**Lincoyan 334**	Rengo 865
Barros Arana & Angol inst. Santo tomás	**Lincoyan 554**	Sagrario Costado Catedral - figure 2
Castellon 1333	Los Carrera 2114	Salas 1533
Castellon 1367	**Maipu 537**	**Salas 445**
Castellon 152	**Maipu 573**	San martin 751 - Inmaculada Concepción
Castellon 520	Maipu & Prat - Edificio Paz	Serrano 568
Caupolican 368	O'Higgins 117	Supermercado campodonico
Caupolican 374	O'Higgins 167	Tucapel 518
Chacabuco 155	O'Higgins 223	Tucapel 606
Cochrane & Prat-hall inst. Virginio Gómez	O'Higgins 236	
Colo-Colo 1334	O'Higgins 340 - Hotel Terrano	

Notes:

Category 1 - 'buildings that was likely to collapse in small earthquakes and therefore have to be demolished'.

Category 2 - 'buildings that might collapse in stronger earthquakes and have to be studied in more detail to see if it is possible to repair them'

Torre O'Higgins 241 (Category 1)

This building in the centre of Concepción suffered extensive damage at several levels. A total of three separate soft storey collapses were identified in this structure as identified by the arrows in Figure 6-5. It is clear that in each case there was a change in shape of the building and it is likely that the changes in building stiffness's at these points contributed to the collapses at these levels.

Figure 6-5: Torre O'Higgins 241. On right the 3 soft storey collapses are identified with the arrows.

Figure 6-6 shows some of the extensive shear damage to the concrete forming the façade. This type of damage was visible around all of the upper storeys of this building. At the time of this report the City Council of Concepcion had decided that the Torre O'Higgins building will be partially demolished, from storey 10 upwards. Their evaluation of the building concluded that the basement and lower floor of the building don't have any damage.

Figure 6-6: Extensive damage to the external façade of Torre O'Higgins 241

Caupolican 518 (Category 1)

This building "Universidad de Concepcion", which was in one of the main shopping districts in the city, did not show a large amount of external damage apart from at one corner (Figure 6-7). Although internal access was not possible, looking through the widows it was clear there had been some damage to many of the internal concrete shear walls at the connections between the tops of the walls and the ceilings. The damage, although apparently not that serious must have been extensive though because the building had been classified as Category 1 i.e. dangerous and in need of demolition. However at the time of this writing this report the original evaluation had been slightly modified and it had been subsequently been decided that only partial demolition of the building was necessary. In this case only the top three levels out of the total of 11 floors will ne demolished.

Figure 6-7: Damage to one corner of Caupolican 518

Lincoyan 440 (Category 1)

This 17 storey residential high-rise concrete building (Figure 6-8) with external shear walls was another structure that had been classified as requiring demolition. Damage was visible at the beam column joints right up the building and where the reinforcement was exposed it was clear that the links spacing was quite wide. There was compression failure of the concrete at the ends of the shear walls and at street level there was significant crushing of the concrete in the shear walls. The extent of internal damage was unclear and it is currently unknown whether this building has actually been demolished.

Figure 6-8: Damage to beam column joints over the full height of Lincoyan 440

Castellon 1367, Castellon 1333, Colo-Colo 1334, Colo-Colo 1372 (Category 2)

This group of four modern buildings "Plaza Mayor I, II, III and IV" (Figure 6-9), were constructed in the years 2002, 2005, 2006 and 2009 respectively. Each building had 14 floors built in reinforced concrete with a garage below ground floor level. The authorities had classified all four buildings as Category 2. All the buildings had been constructed by the same construction company and real estate company with new short lease flats in Plaza Mayor IV being advertised with banners on that building when the team visited.

The oldest of the four buildings (Plaza Mayor I) suffered the most damage. Figure 6-9 shows some of the typical damage to the building. In particular there was extensive damage to outstands around the projecting window openings with much of the glazing in these windows apparently having been shattered by the deformation of the concrete around the windows. The concrete in these projections being only lightly reinforced with poor connections details and very few relatively small links.

Figure 6-9: Plaza Mayor I (2002) showing extensive damage around projecting windows.

In addition to the damage around the windows there was significant damage to the columns (Figure 6-10 left) and some short shear walls (Figure 6-10 right) at the 1st floor level where the building shape changed with the addition of the entrance to the building reception. Similar but less extensive damage was noted at other locations at ground level.

Figure 6-10: Failures to Plaza Mayor I at 1st floor level. Left: Buckling of steel and loss of cover in column elements, Right: lack of links in shear wall elements

Interestingly Plaza Mayor II (Figure 6-11), and Plaza Major III showed relatively little external damage but the most recent building Plaza Major IV showed sign of extensive damage right to the top of the building. Looking at the detailing of the beam column joints (Figure 6-12), where no continuous vertical reinforcement is visible, it is possible that this building was formed from precast panels with an internal frame rather than being a typical RC building with shear walls like the other 3 in the group. It was not possible to enter this building however to confirm the construction.

Figure 6-11: Minor external damage to Plaza Mayor II (left), Detail of cracking of shear walls in Plaza Mayor III (right)

Figure 6-12: Damage up the full height of Plaza Mayor IV (left), Detail of beam column connection in Plaza Mayor IV (right).

Salas 445

This 24 storey building with a basement showed significant damage to the exterior shear walls (Figure 6-13). In particular, concrete crushing and buckled reinforcement was evident in shear wall (top right Figure 6-13) at the rear of the building adjacent to the entrance ramp leading down to the basement. At the font of the building (bottom images in Figure 6-13) another of the main shear walls was badly damaged but in this case the failure appeared to be at a construction joint. Several of the main tension reinforcement bars had been terminated at this point and the horizontal joint between the two concrete pours is clearly visible.

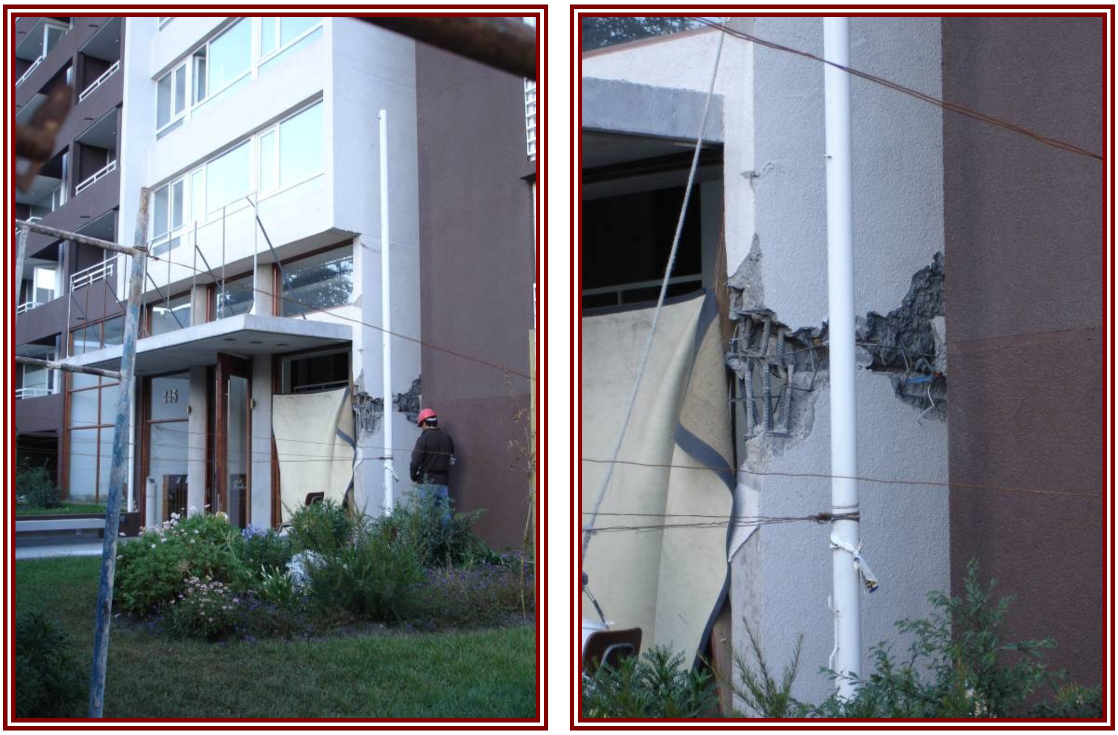

Figure 6-13: Views of the damage to Salas 445

<ins>Anibol Pinto 820</ins>

This building (Figure 6-14) was typical of the many smaller concrete framed buildings that the team observed throughout Concepción that had not been included on the list produced by the City Council. Although very badly damaged the building was still occupied when the team visited and was still being used as a business premises. The main 16mm reinforcement in the frame were smooth rather than ribbed with 6mm links at about 150 mm centres and a plastic hinge had formed at the top of every column where it connected to the floor beam above.

Figure 6-14: Views of the damage to Anibol Pinto 820

<ins>The 12 storey Torre Alto Rio Building and the building at Maipu & Arturo Prat</ins>

The 12 storey Torre Alto Rio Building was one of the more unusual building collapses seen by the team in Concepción. The building (Figure 6-15, Figure 6-16, Figure 6-17) had toppled over with the building falling Northward and then splitting in half. It was not clear what the cause of failure was although it may have been related to the ground conditions. In this case the building was designed for soil type II according to the Chilean code. It is not known what the ground conditions at the site are but it is worth noting that the building was relatively close (600m) to the shoreline of the Biobio river and the tall building at the junction of Maipu & Arturo Prat (seen in the background of Figure 6-

16) was designed for soil III. This tall apartment building at the corner of Maipu & Arturo Prat which had only just been completed also suffered some damage especially to the ground floor level. Subsequent to the visit the team has learnt that this building will probably be demolished because of the extent of damage. In the case of the Torre Alto Rio Building, because there were several casualties, it is believed that there will be a number of forensic analyses to try to determine the exact cause of collapse.

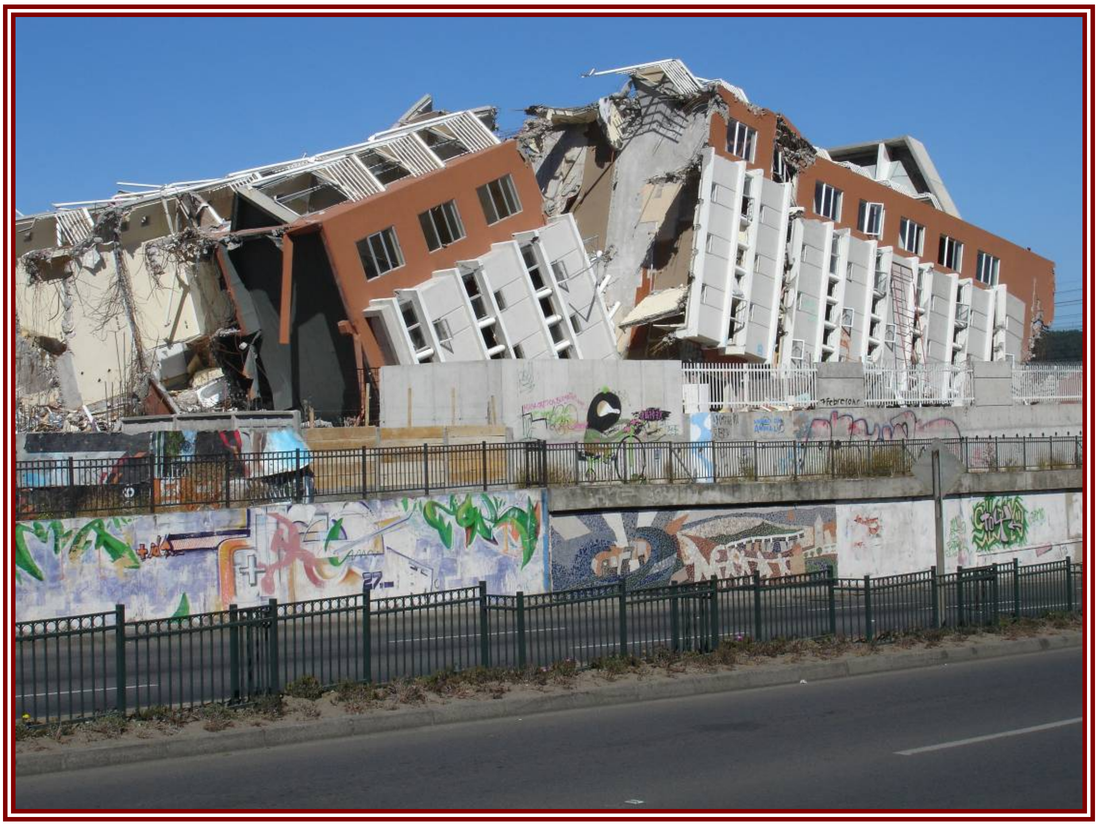

Figure 6-15: The collapsed Torre Alto Rio (collapsed towards photographer)

Figure 6-16: Torre Alto Rio (collapsed away from photographer)

Figure 6-17: Torre Alto Rio. View of 1st floor ceiling (left), Detail of remains of 1st floor columns at foundation level (right)

6.4.2 Modern Buildings in Talcahuano

Arturoi Prat 88, Talcahuano

This RC concrete building on the coast at Talcahuano is believed to be about 60 years old and is formed from two very similar buildings with a joint down the middle. The building had a two storey basement that had been filled with water by the tsunami. All the columns at 1st floor level on one half of the building were very badly damaged while the other half of the building remained relatively intact. At the time of this writing this report this building is in the process of being demolished.

Figure 6-18: Arturoi Prat 88, Talcahuano

Liceo A21 Blanco Encalada, Talcahuano

This large concrete building school building right on the coast at Talcahuano had been damaged both by the tsunami and by the earthquake. The main section of the school was constructed as a concrete frame (Figure 6-19 left) with small masonry infill panels and this performed well in the earthquake. However the square tower (Figure 6-19 right) that formed the entrance to the building performed much less well. This entrance building with half of one face being glazed over its full height was constructed from confined masonry and it may have been the asymmetry of the building that lead to the severe damage at one corner and the loss of a large masonry panel.

Figure 6-19: Liceo A21 Blanco Encalada, Talcahuano

6.5 Roads and Bridges

Figure 6-20: Bridge locations observed on the drive south. (Red – span(s) collapsed, Yellow - damaged, Green – appeared undamaged, Blue – severe settlement of road)

The majority of damaged bridges seen down route 5 were precast concrete bridges but there were a few exceptions. In a few places the predominantly steel bridges for the main railway line (Figure 6-21) running close to route 5 were also badly damaged, however no failures of the steel were noted and most damage appeared to be at the bearings. Just south of Chillan a small length of one of the central sections of an older in-situ concrete bridge had collapsed (Figure 6-22). In this case the points of failure were not over supports and it appears as if the concrete section has failed in shear (possibly at construction joints). Again it is worth noting that along route 5 the northbound and southbound carriageways often ran across rivers on two separate parallel bridges. One of these bridges being an older 2 lane bridge, and the second an extra bridge that was built (after 1994) to carry an extra carriageway when the route 5 was widened to two lanes each direction. Therefore although many individual bridges had spans down the team saw no cases where both bridges were damaged. This had allowed route 5 to remain open with traffic being rerouted to the remaining intact bridge.

Figure 6-21: Badly damaged railway bridge

Figure 6-22: Collapsed skew span

6.5.1 The four bridges across the Biobío river

The 1869m Puente Viejo bridge (Old Bridge) (Figure 6-23) built in 1943 is the oldest of the three road bridges across the Biobío river from Concepción to San Pedro de la Paz. It was closed to road traffic in 2002 as it was deemed to be a safety risk in the highly seismic area, although it remained in use as a pedestrian bridge. During this earthquake the bridge suffered major damage with the collapse of multiple spans. The bridge was in a poor state of repair, much of the steelwork was badly corroded (Figure 6-24) and many of the expansion joints (over every support) had been filled with tarmac which showed signs that there had been significant longitudinal movement of the deck during the earthquake. There was evidence of considerable lateral spreading of the north bank of the river at this location with cracks appearing in the ground up to 70m from the shoreline (Figure 6-25).

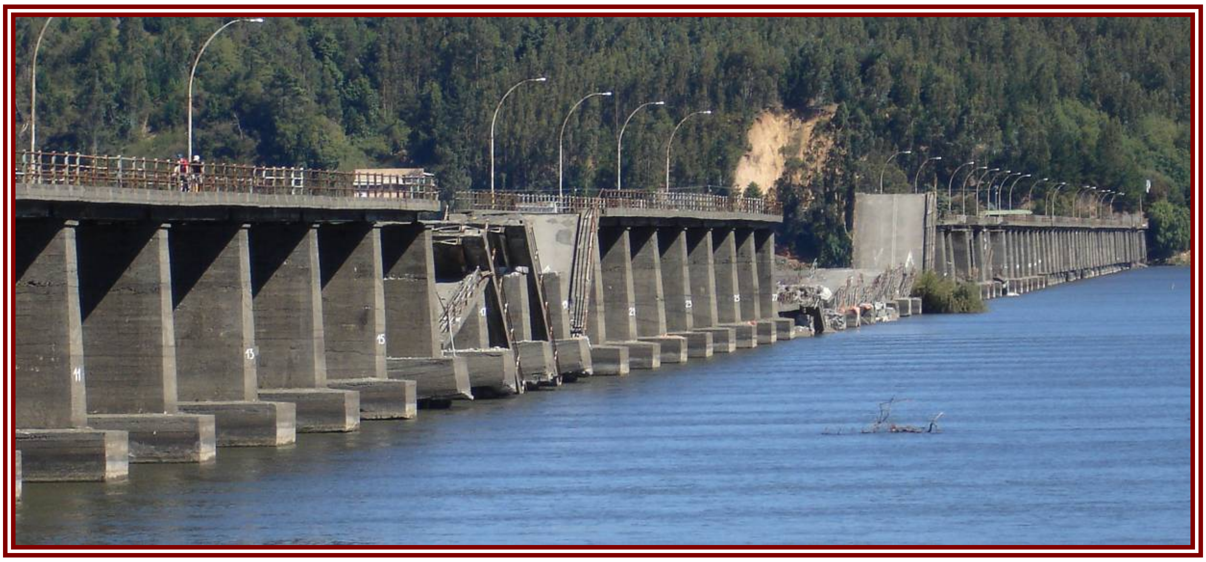

Figure 6-23: Collapsed spans in the Puente Viejo Bridge in Concepción

Figure 6-24: Span failure in the Puente Viejo Bridge

Figure 6-25: Evidence of lateral spreading on the north bank of Biobío river

Figure 6-26: Collapsed approach span on the Llacolen bridge

Figure 6-27: Signs of pier settlement on the Juan Pablo II bridge

The nearby 2157 m Llacolen (2000) bridge (Figure 6-26) suffered damage to one approach span reducing the traffic to one lane after the earthquake, again signs of lateral spreading were evident on the north bank of the bridge. The Juan Pablo II (1968) bridge (Figure-6-27) was constructed in response to the the growth of habitants in San Pedro de la Paz and also showed signs of settlement to some of the supports mid-river. Although the bridge remained open when the team visited this bridge has subsequently been is closed because of its risk of imminent failure. Evidence of liquefaction was observed as sand boils on the north bank of the bridge, which can explain the settlement and lateral displacement. In all these three cases it looked as if lateral spreading and possibly liquefaction contributed to the damage to the bridges which are situated on the sandy sediments of Bio-Bio River (Figures 6-23 to 6-27). No obvious signs of damage were observed to the steel truss Biobío Railroad Bridge (1889).

The Chilean Code of Practice for Seismic Design NCh 433.Of96 defines liquefiable soils as "saturated silty sands and silts with a Standard Penetration Resistance number N less than 20, normalized to an effective overburden pressure of 0.10 Mpa. The strong PGA recorded near the city and the long duration of the event generated liquefaction in the coast regions of the Bio-Bio river. The type of soil considered in this area amplifies the shear waves, and the presence of silty layers induces a higher increase of pore pressure in the sandy soil layers. Although liquefaction may not been observed superficially in some areas, it can occur at higher depths producing settlement and damage to structures and this may have been the case for these bridges. The Chilean Code doesn't consider design in difficult soils like liquefiable ones or those susceptible of densification due to vibration. In addition, many methods for analysis of liquefaction are not applicable to high seismic magnitudes as was the case in this earthquake. Finally there are also potential problems with sandy soils containing a high fines content (i.e. over 20% of silts and/or 35% of clay) because the methodologies currently used to estimate the depth of liquefaction are generally not applicable and can overestimate their resistance to liquefaction. In an earthquake such as this the high ground motions can produce soil softening even in these soils which can lead to geotechnical failures.

6.6 Coasts & Ports

Lateral spreading and longitudinal cracks (Figure 6-28) and the displacement of retaining walls along the coast of Talcahuano (Figure 6-29) were probably produced by the increase in pore water pressure in the soil due to the tsunami.

Figure 6-28: Longitudinal cracks Talcahuano Port

Figure 6-29: Retaining wall failure Talcahuano Port

Several ships at Talcahuano port were lifted onto the dockside by the tsunami (Figure 6-30) and hundreds of containers were also moved causing structural damage to buildings due to impact. These containers were scattered about the coastline of the bay and some had drifted large distances. Scour damage to building foundations along the waterfront was a very common occurrence (Figure 6-31).

Figure 6-30: Vessels several metres inland

Figure 6-31: Scour damage to building foundation

The main naval base is located in Talcahuano, and while we could not gain access to the facility, damage was clear from our position outside the base. A large stretch of Talcahuano's seafront was still closed off to the general public around the container facilities so we were unable to make an assessment of this area. Earthquake damage was also abundant in the buildings around the port with several severely damaged.

Further along the bay the port of Penco also experienced damage from the tsunami. Part of the team briefly visited the town and noted similar inundation damage as elsewhere on the coast. The JSCE team measured a run-up value of 5.25 metres so this is consistent with other locations.

North of Penco still inside the bay, the town of Tomé managed to escape the full force of the tsunami. Most damage here appeared to be due to the earthquake, though some structures showed signs of the inundation which quite visibly had occurred with a height of several metres.

Further north of Tomé the next much smaller bay contains the towns of Coliumo and Dichato on the west and east sides respectively. This bay was severely affected by the tsunami and had measured run-up heights of up to 9 metres above mean sea level which was above the tops of many of the structures. Eye witnesses say Dichato was inundated by turbulent water carrying shipping containers, boats and buoyant buildings. Impacts from the floating debris caused a lot of the structural failures in Dichato. The water inundated 600m inland in Dichato town causing severe structural damage almost to the high water level.

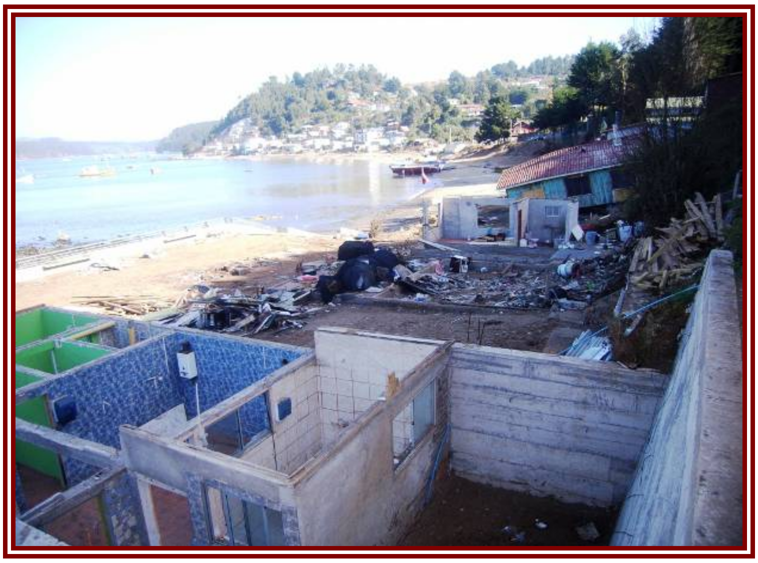

Figure 6-32: Damage to water front, Coliumo

Figure 6-33: Damage to house and road, Dichato

As can be seen, scour once again was a source of failures on this very sandy soil (Figure 6-33). In places buildings were completely undermined by the strong currents generated. The small structures shown in Figure 6-34were 400 metres from the beach.

Figure 6-34: Damage to rows of housing, and tall structure, Dichato

The eight story structures in Figure 6-34 are a relative success story. Access was not permitted, but interviewing the guard revealed the building's basement, ground and first floors were uninhabitable due to water damage, but the higher floors were undamaged. The buildings had no structural issues. The red arrow on Figure 6-34 shows the high water inundation mark at the top of the first floor of the nearest building.

6.7 Industrial

6.7.1 Silo Collapse, Concepción

At the junction of Manuel Montt and Miguel Zanãrtu was a complex of 14 grain silos (Figure 6-35) that was badly damaged during the earthquake. The site originally comprised 4 larger silos and 10 smaller silos, Figure 6-19. After the earthquake the silos that remained standing were generally those that had a more significant restraint at their tops, figure 6-18. Those silos that were essentially free standing collapsed completely or were very badly damaged (Figure 6-36). The silos that remained standing were also of different construction (riveted solid plates with two intermediate external stiffening rings) compared to those that had collapsed (light weight cold formed ribbed panels with bolted connections). It appears that the site had been extended with the addition of 9 extra silos at some time in the past and it was these more recent additions that performed very badly.

Figure 6-35: Damage to a complex of 14 grain silos showing severe bucking of one of the remaining silos. Differences in the construction of silos are also apparent.

Figure 6-36: Aerial photo of site before earthquake, ringed silos appeared to be original

Figure 6-37: Leaning silo and damaged grain conveyor

7 Use of satellite imagery for post-earthquake disaster assessment

The Virtual Disaster Viewer, (VDV) is a web based product developed by ImageCat for EEFIT and EERI, with the aim of using pre and post satellite imagery, to identify and assess seismic damage after a destructive event. VDV was initially developed for the 2008 China earthquake and through EPSRC funding has been extended for the 2009 L'Aquila Italian earthquake, the 2009 South Pacific earthquake and tsunami, and the 2009 Padang, Indonesia earthquake.

For the purpose of the EEFIT Chile Mission, several upgrades where required, such as digital photographs upload, tagging and classification, extended and improved "User generated layers" , enhanced interface with Google Earth environment.

The final updated product was delivered by September 2010. Effort were also made to enhance the quality of the satellite imagery available and the speed of uploading and handling large numbers of vertical images and refreshing of imagery layers.

7.1 Field data imagery upload

During the mission all the photographs were geotagged, either using cameras with inbuilt GPS or using separate GPS units that were synchronised with the camera timestamps on the photos. On return to the UK this data set was collected and the images categorized according to Object, Object Type and Damage level. This was the first EEFIT mission where this level of detailed classification of photographs was done and there are now more than 2800 photographs publically assessable at http://www.virtualdisasterviewer.com/vdv/ along with high resolution satellite imagery of the main cities where damage was severe. To enable this upload of categorized photographs to the Virtual Disaster Viewer (VDV) website the website database was extensively modified to allow the upload along with suitable searching and viewing of the categorized photographs. The classification system developed for VDV (Table 7-1) was extended from HAZUS to cover a slightly wider range of object types enabling the future use of VDV with a wide range of different types of event.

Table 7-1: VDV Classification of Field Photos

Object	Object type (extended from HAZUS)	Damage level (from EMS-98)	Comments
Buildings	Timber / Woodframe Steel Concrete Precast Reinforced masonry Unreinforced masonry Confined Masonry Manufactured housing Adobe Composite Other Unknown	No damage Slight Moderate Heavy Total destruction	*e.g.* *Concrete Frame with Unreinforced Masonry Infill* *Concrete Shear Walls* *Soft storey failure at 2nd floor level* *Rubble stone building* *Base isolated concrete shear wall building* *Storage tanks at winery*
Infrastructure	Bridge Dam Dock walls / piers Other		
Transport	Highway Railway Light rail Bus Ferry Port Airport Other		
Key Facilities	Hospital School		

	EOC (emergency operations centre) Police station Fire station IDP camp Religious building Public building Other
Utilities	Potable water Waste water Natural gas Oil system Electrical power lines Communication Power plant Other
Terrain	Landslide Liquefaction Lateral Spreading Surface faulting Rockfall Differential Settlement Other
Other	Tsunami Flood Fire Other

An example of a typical search of the data set is shown in Figure 2-6, where the building types for damaged structures in part of Concepción can be seen. This type of classification of the photographs has been very useful during post event analysis of aerial photography which has tried to verify if aerial imaging analysis can aid in the decision making process of identifying structures to be demolished from structures to be repaired.

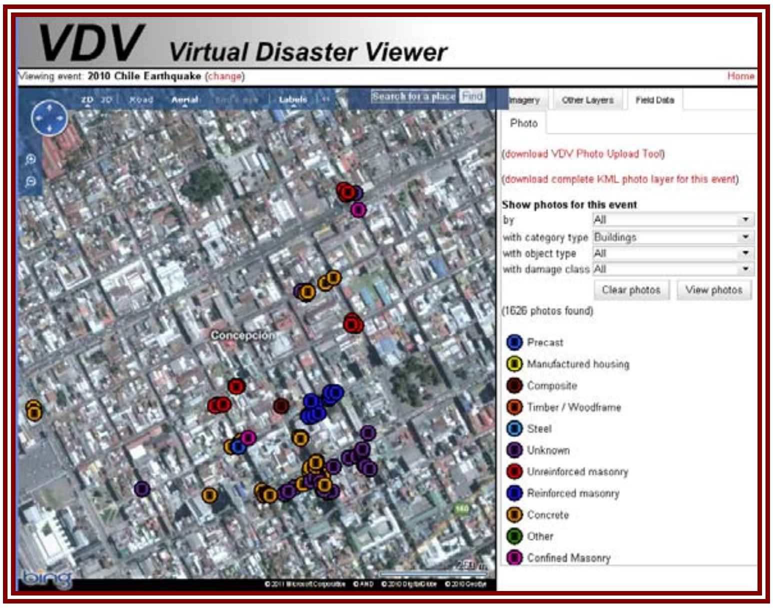

Figure 7-1: Screen shot from VDV (http://www.virtualdisasterviewer.com/vdv/) showing buildings in Concepción that were investigated classified by building type.

Although the process of categorizing and uploading a large number of photographs proved to be relatively time-consuming it has enabled much easier interpretation of the resulting set of photographs and if is certainly recommended that any future EEFIT missions should try to process their photographs in a similar way in the future.

7.2 Earthquake damage detection and assessment

To improve the ease of analysis of satellite imagery VDV was also extended to allow the team to add user generated information to the imagery layers. VDV now has the option for users to draw points, lines or any shaped polygons over any of the pre or post event satellite imagery.

The damage analysis was carried out for the two sities of Constitución and Conception which both had seismic and tsunami extensive damage. The available imagery was Quickbird2 'before' and Worldview1 50cm greyscale 'after' image, covering 95% of urban area, for Constitución and Bing 'before' and Quickbird2 60cm colour 'after' image, covering all of main urban area for Conception. The consequences of using different image product and resolution for the earthquake damage detection are discussed in detail in the following.

As the Figure 7-2 shows, before starting the damage reconnaissance, the area of Constitución has been divided in different urban blocks by drawing red lines which delimit the edges of each block by the main street grid; the purpose was to frame the blocks with large amount of damage and to then refer the damaged surface area to the surface area of the block. However the measuring tool of the VDV was only developed at a later stage during the project so only some of the polygons have measured surface as an attribute.

Once all the blocks where damage is expected have been framed, the damage assessment is achieved by comparing the satellite photography of the pre and post earthquake event provided by the VDV web portal.

Figure 7-2 Constitución - Pre- and post- event satellite images of the site damaged by tsunami

The pre and post earthquake satellite images of Constitución are particularly sharp and their comparison is sufficient to localise and identify the damage..

The most easily identifiable damage in the post earthquake satellite image is due to the tsunami; which is concentrated along the river estuary of Constitución . In order to highlight the tsunami damage all buildings of this area that survived the energy released by the seismic sea waves are framed in orange by using the tool "polygon" provided by the VDV web portal, as the Figure 7-3 illustrates.

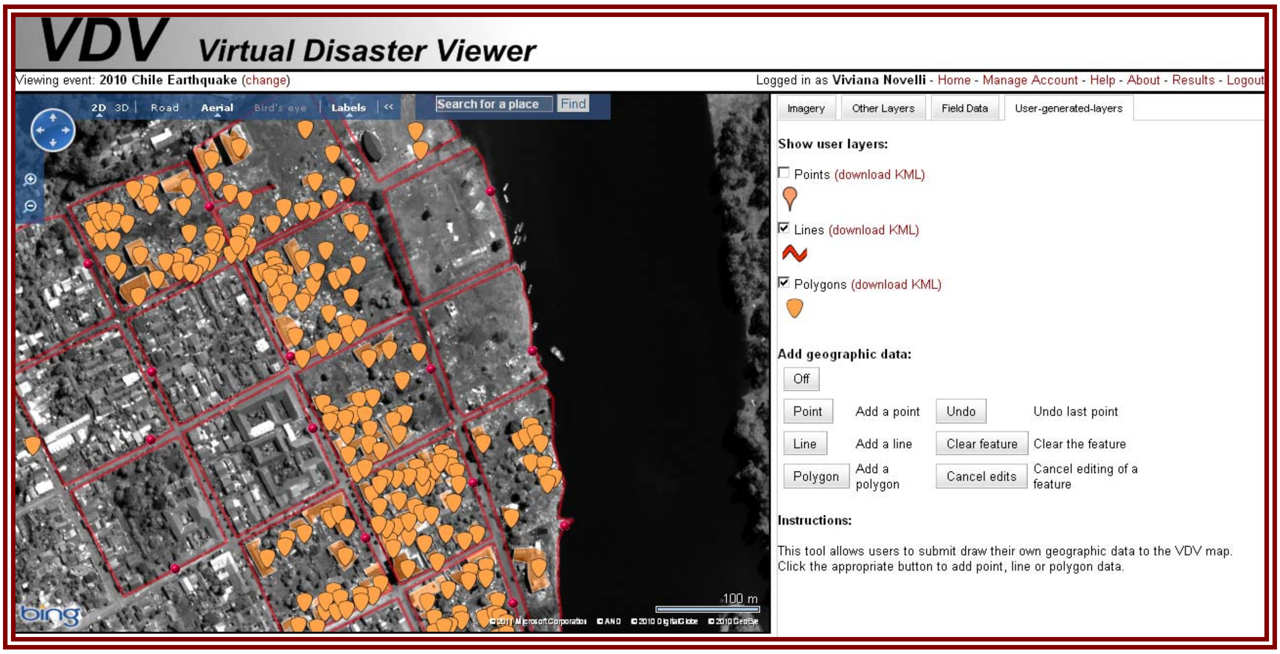

Figure 7-3 Constitución - Mapping of the buildings survived to the tsunami

Moving inland from the estuary, several other blocks where strong motion shaking damage occurred were identified and also framed in red, as the VDV only allows for one colour per drawing feature (point in orange, lines in red, polygons in orange) , (see the Figure 7-4), Within those blocks only the damaged buildings were highlighted with the tool “polygon”, see the Figure 7-5,. as they represent a minority within each block.

From the post event satellite image, the type of failure of the vertical structure of the inspected buildings can not been identified; indeed only high level damage relative to top horizontal surface collapse and partial and total collapse of a building can be recognised.

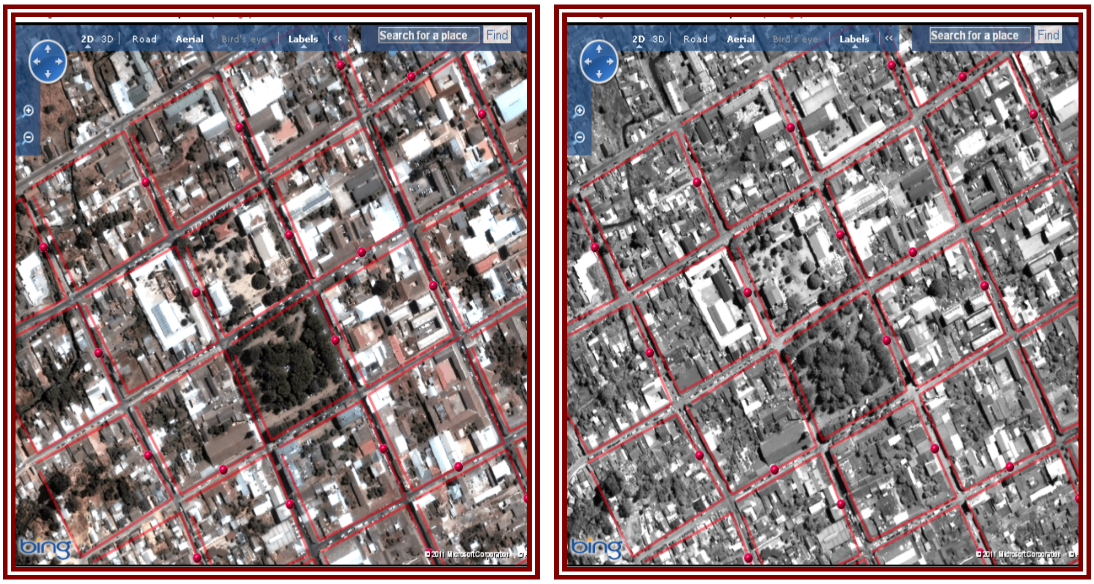

Figure 7-4 Constitución - Pre-post event satellite image of the site damaged by the earthquake

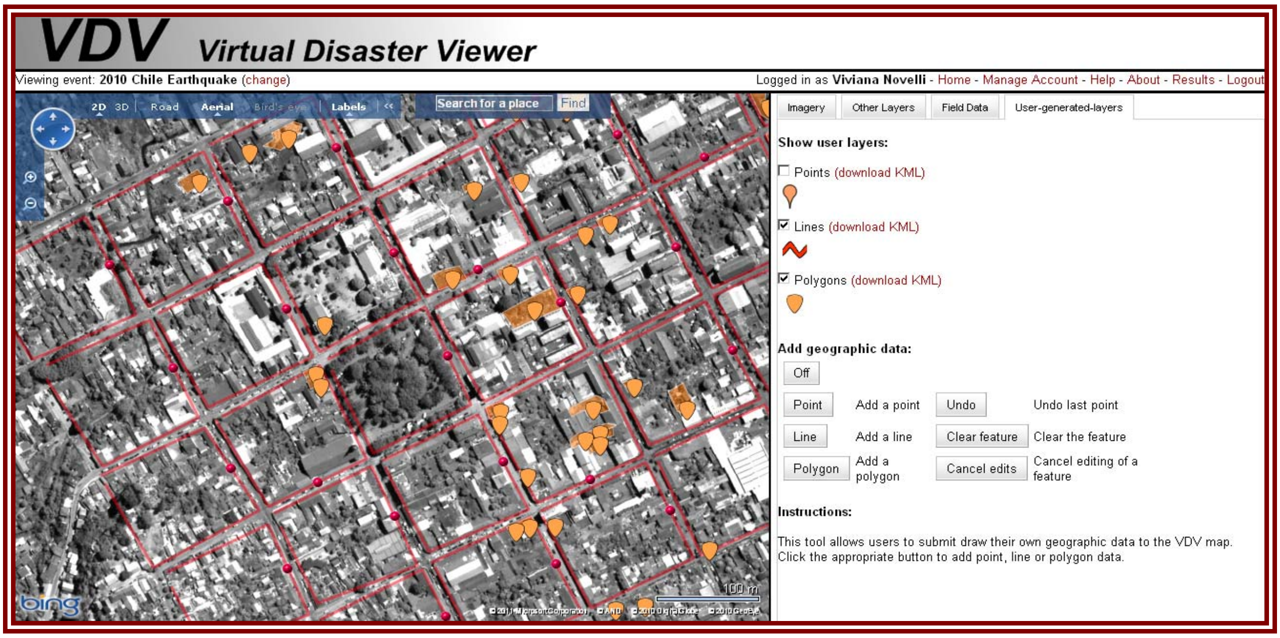

Figure 7-5 Constitución - Mapping of the buildings damaged by the earthquake

The large number of vertical images uploaded in the VDV web portal (as the Figure 7-6 shows) were used to validate the damage identification carried out using the satellite imagery. However, the vertical images are usually geo-referenced from the position of the photographer rather than the object itself, in some case creating confusion over the correct assignment of the satellite image corresponding building. A useful tool would be a symbol which points out the direction in which each picture has been taken; this expedient would help the user to identify the building of the picture on the post event satellite image.

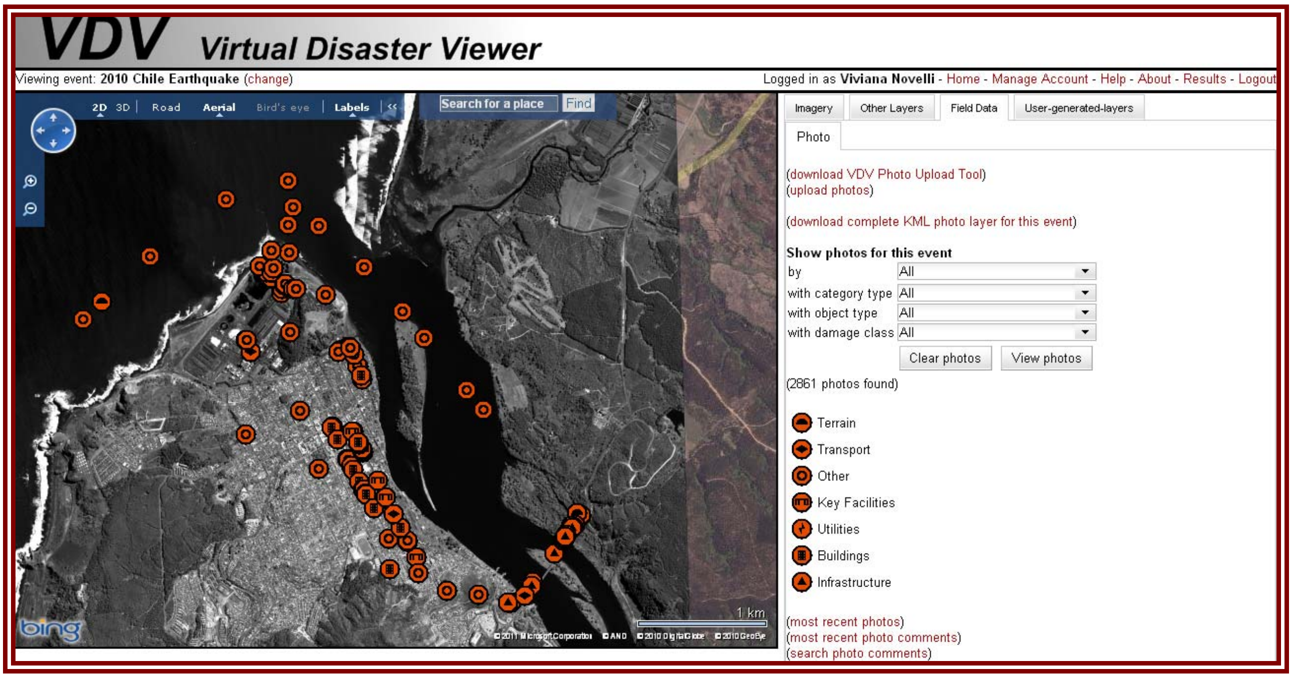

Figure 7-6 Constitución - Mapping of the vertical images

For the area of Conception the seismic and tsunami damage identification is difficult to assess since the quality of the satellite images is low and the colours of the post event satellite image are so bright that it is extremely hard to identify the edges of volumes and hence recognise possibly damaged buildings (see Figure 7-7. Moreover the uploaded vertical images in this area suffer from the same geo-referencing shortfall than previously mentioned for Constitución , hence being unhelpful in identifying positively damaged buildings.

Figure 7-7 Conception - Pre-post event satellite image

In conclusion, the VDV web portal can be considered an interesting tool for looking at damage occurred on buildings due to earthquake and or tsunami by comparing satellite imagine before and after earthquake-event and vertical imagery collected on site. However the current version of this device still needs substantial developments which can be identified as follows:

- Correct collocation of vertical images and use of symbols for identifying the direction in which a picture has been taken
- Development of tools able to change colours of points, lines, or polygons
- Improvement of satellite image quality or more careful choice of purchased satellite imagery
- Development of tools able to measure perimeters of polygons and length of lines.

8 Conclusions

8.1 *Site Effects*

Factors influencing site effects can include the modifications of the vibrating signal due to the terrain and superficial layers and the effects of morphologic and hydrological factors that the earthquake has over the soil (liquefaction, slides and landslide). The sedimentology and stratigraphic characteristics of the soil deposit or rock, the presence of faults and ruptures, depth of water table, the absence or presence of an artificial overfill and topographic slope can produce several site effects.

The city centre of Concepción, where many of the damaged buildings are situated, is filled by artificial overfill sandy sediments with loose to medium density, inducing site amplification. The hills that surround this area are mostly composed by clayey sand (local name: *maicillo*) and stiff clay, without presenting slides or landslides. The presence of different vertical faults which cross Concepción and Talcahuano, increases site effects and localized damage to structures. The lack of knowledge of the exact location and depth of these faults forces the authorities to be cautious and discard high buildings and roads near the probable locations, but this seems not to be taken into consideration by the building companies. This was one of the explanations that the building company of "Alto Rio" (totally collapsed building) gave to the authorities, saying that a probable fault crosses the area were the building was constructed. The proximity to the river Bio-Bio gives an average depth of the water table of 2 and 5 for February and July respectively, increasing the probability of soil liquefaction and lateral spreading, phenomena observed in the entire river BioBio coast near the city.

The 1985 Valparaiso earthquake revealed site effects in the Santiago basin, due to unconsolidated sediments at shallow depths. The evidence of expansive clays localized in Santiago increases seismic amplification in the area. The recent earthquake also revealed a normal fault in the Maipo River Valley, in east side of the city, with a longitudinal crack reaching 4 km of extension, destroying houses and elevating the land over 0.50 m.

8.1.1 Soil Conditions:

Santiago city located in Region Metropolitana, 400 km from the earthquake epicentre, is characterized by a morph-structural unit generated during the Medium Superior Oligocene – Pliocene Era. The plane area where the city of Santiago is located is filled principally by landfill alluvial sediments and in less proportion by volcanic sediments. Specifically the areas of Pudahuel and Maipu are covered by superficial layer of volcanic sediments. This landfill has been recognized by boreholes of 120 m. of depth. The last meters of landfill are alluvial-fluvial sediments coming from the rivers Maipo and Mapocho. The Santiago basin has a wide variety of geological formations generated by different disintegration processes. The soil profile of Santiago is mainly made of sandy clay, sandy gravel and clayey gravel reaching more than 30 m. of depth, with some intermediate layers of sand and clay. The seismic classification given to these soils are Category II and III according to the Code of Practice of Chile "Seismic Design of Buildings NCh 433.Of96. Table 2-3 gives the definition of these categories. There is also evidence of some expansive clay in the Santiago basin, most of them located near the Mountain chain area.

VI Region General Bernardo O'Higgins and VII Region Maule where the epicentre was located are dominated by clays in the intermediate area between the Coast Mountains and Los Andes Mountains. In the Andes Mountains the most characteristic soil is composed by volcanic ashes. In the south area of Region Maule the presence of fluvial-glacial sediments gives more internal drainage to the soil. Between the rivers Maule and Perquilauquen alluvial soils have variable grains size and profile. In all the valleys there are granitic and coluvial sediments, stratified, plane deposition, deep, and with low permeability, high quartz and mica content. Specifically in Talca City there are mainly fluvial sediments with grains size increasing with depth, between silt, sand and gravel. The majority of these soils are classified as II.

Region Del Biobío, specifically the city of Concepción, 115 km from the epicentre, is formed by sediments carried from the Andes Mountains by the river Biobío. Concepción and Talcahuano city areas are furrowed by vertical faults which act as a tectonic unit producing relative displacements with seismic events. The soil is predominantly sand with interleaving of silt-clay, composed primarily by medium sands, uniform and with variable percentage of silt; the density varies between loose and very dense, increasing with depth and reaching a maximum thickness of 107 m. in the city centre of Concepción. The silty-clay layers have a variable distribution, depending on the location. In the City Centre of Concepción they are located at 20 m of depth; near the rivers and hills this layers are more superficial and relevant; generally they contain organic material and variable mechanical properties. In all the Concepción and Talcahuano area there is a superficial layer of overfill loose sand with SPT number less than 20 blows/ft. with thickness varying in general between 3 and 7 meters. Most of the soil in the city is classified as III (Figure 8-1) which correspond to silty sand, classified as SM in the USCS Classification System.

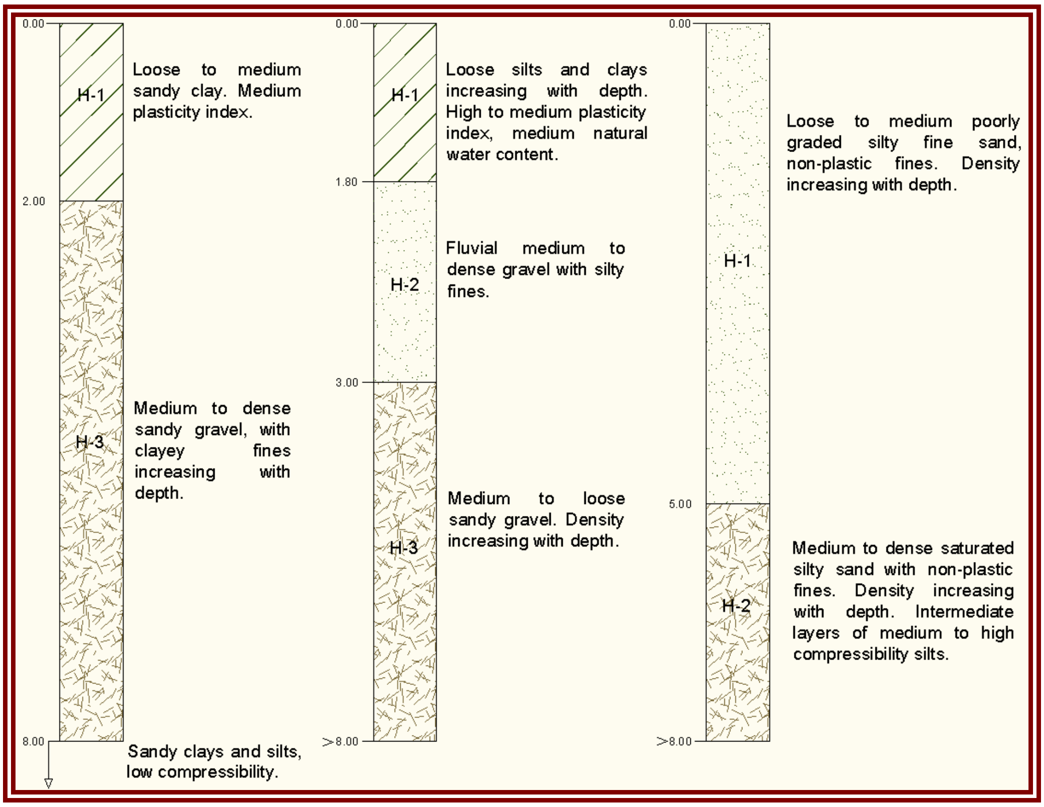

Figure 8-1: General Soil profile for the city centre of (a) Santiago, (b) Talca, and (c) Concepción.

8.1.2 Geotechnical Aspects:

Lateral spreading, strong motion and liquefaction can explain the damage of the two bridges in Concepción which are situated over the sandy sediments of Bio-Bio River, joining Concepción to San Pedro de la Paz city.

The railway bridge located between these two cities was constructed in 1890, and didn't suffer any damage. The "Puente Viejo" bridge, with 1648.5 m. of length was inaugurated in 1943, and recently it was been studied for its reparation, but was only in use for pedestrians. With the recent earthquake it collapsed completely.

With the growth of habitants in San Pedro de la Paz a new bridge was constructed in 1968 called "Juan Pablo II", this bridge suffered settlement in the middle area of its extension, and it is closed because of its imminent collapse. This settlement can be a cause of liquefaction, due to the presence of saturated non-cohesive loose clean sand in the river Biobío.

In February of 2000 the "Llacolen" bridge was inaugurated with 2157 m. of extension designed for urban traffic. The bridge collapsed in a section with the strong motion of the earthquake.

The large crack observed in the ends of the bridges and in the coast of the river evidence the clearly the lateral spreading generated and the loose conditions of the sand.

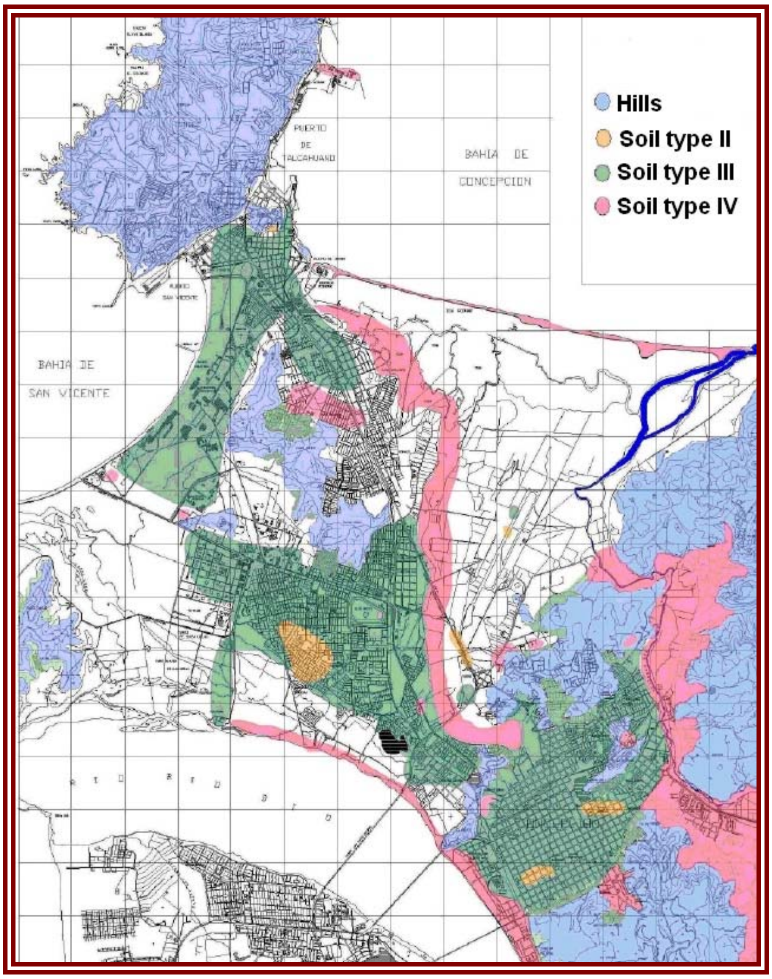

Figure 8-2: Geotechnical Map of Concepción and Talcahuano city, according to Table 2-3 (Valenzuela et al. 2007)

The Chilean Code of Practice for Seismic Design NCh 433.Of96 defines liquefiable soils as “saturated silty sands and silts with a Standard Penetration Resistance number N less than 20, normalized to an effective overburden pressure of 0.10 Mpa. This Code doesn’t consider the design in difficult soils like liquefiable soils or those susceptible of densification due to vibration, so the Geotechnical engineer must find a soil stratigraphy that gives the major basal shear stress.

Figure 8-3: Evidence of liquefaction near the Bio-Bio River in Concepción. http://poweredbyorange.com/blog/

Other important aspect observed in Concepción was the damage in the pedestrian paths which had several settlements, not more than 0.30 m., the majority caused by the destruction of water pipelines.

Figure 8-4: Settlement due to water pipeline damage, city of Concepción.

8.2 Tsunami

In the days and weeks following the 27 February 2010 event, there were very few reports of the tsunami in the international media. An overwhelming majority of reports focussed almost exclusively on earthquake damage and for some reason the tsunami went by almost unnoticed by the outside world. In some areas of the Chile the tsunami accounts for the majority of the structural damage, and though a final figure on the death toll has not been reached, it is assumed by most that the tsunami accounts for the majority of fatalities resulting from this event overall. Many are still listed as missing. Reasons for the initial lack of information are unclear, but certainly on the basis of what has been seen by the team, a large series of tsunami inundated a long expanse of coastline with very significant inundation depths and run-up heights.

Figure 8-5: Timber top floor survived undamaged despite being completely submerged

Structural damage observed included scour and undermining of foundations, impact by floating debris, failure to resist hydrodynamic, overturning, and buoyancy forces. As is sometimes the case, well built engineered reinforced concrete structures generally fared better than other forms of construction. Timber frames are a popular choice on the coast and occasionally a timber top floor with a reinforced concrete or masonry ground floor are constructed. In this case the team often observed the ground floor intact structurally, but the first floor had been lost. The type of anchoring of the top floor to the base in this type of construction is generally insufficient to resist the level of loading expected from a tsunami and as such structures of this type often fail.

There was one notable example observed in Dichato of this type of construction that survived (**Error! Reference source not found.**). The owner had built the ground floor base out of very good quality reinforced concrete and anchored the hardwood first floor to the base using three foot starter bars from the walls. He had also taken the liberty of installing a modest reinforced concrete sea wall immediately in front of his building. Incredibly though the water reached the top of the roof, there had only been blow out of windows and obviously loss of contents. Structurally, the building was sound. The proximity to the waterfront is clear, so this makes the story all the more impressive.

8.3 Historical & Vernacular Buildings

Heritage buildings in Chile are mainly built of timber and masonry of either stonework or adobe, with a minority of cases in fired brickwork. The Chilean code does not currently include prescriptions for repair or strengthening of these classes of buildings or provides requirement for new construction in these materials, which could be used as reference to assess their performance in this event. Rather, adobe as a construction material has been banned since the 1960 earthquake, while brickwork is allowed for new construction only if adequately reinforced or confined.

These requirements have led to two different attitudes towards heritage construction: either demolition or heavy handed strengthening. Among the historic buildings visited during the mission, the majority was listed as either national or historic monument. In Santiago only a minority of the visited buildings had been retrofitted in any evident way. In Talca where much of the historic buildings were destroyed by the 1928 earthquake, many of the major monuments have been rebuilt making extensive use of confined masonry for the vertical structures and reinforced concrete for slabs and roofs. Although damage was not altogether prevented in these buildings, it was certainly contained, when compared with the performance of buildings in the historic villages.

The churches visited in the villages of the Valle de Colchagua had a common 3 aisles typology and had all been damaged in past earthquakes and strengthen to different extent in recent years. Most common intervention had been the shotcreting of all longitudinal adobe walls, although this not always implemented in conjunction with wire mesh and through thickness ties. In general shotcreting has not been sufficient to prevent cracking and partial collapse of the adobe walls. The general lateral stability of the churches is the main issue, considering substantial difference in lateral flexibility of the internal timber colonnades and the external longitudinal adobe walls. Facades collapse has been in general less of an issue. This behaviour is also common to churches of similar typology visited by the author in Peru' and affected by the Pisco 2007 earthquake.

The building stock of the villages of the Valle of Colchagua is mainly made of one storey adobe houses with few two storeys exceptions. Many of the historic ones are made of a succession of rooms in line with a courtyard at the back and a porch at the front. The roof has a ridge beam spanning from end wall to end wall or partition wall and rafter resting on this and the longitudinal walls. The older buildings are built in line along the high street and sometimes share end walls. The stability and three dimensional box behaviour of the building is enhanced by the portico and the connection between rafters and wall plate is essential in ensuring restraining out of plane mechanisms in the adobe wall.

Adobes buildings in general need demanding maintenance routine to prevent rotting from water penetration and pulverisation of the adobe due to termites attack. In many cases the completely collapse buildings suffered from loss of integrity of the adobe material and their bearing and lateral capacity had hence been significantly compromised before the earthquake.

Some of the building inspected in Lolol and other small villages, although not irreparably damaged had been listed for demolition at the time of the visit and much of this had already been carried on in Peralillo and other small centres. The reason given was that due to the poor conservation condition and lack of resources people felt no confident in keep inhabiting them. If the demolition has been carried out as extensively as planned many historic high street and village main square will be completely raised to the floor and rebuilt in coming years.

In order to counteract this attitude, numerous initiatives to promote the safer repair and preservation of adobe heritage buildings were initiated in the immediate aftermath of the earthquake. Among those the Centro Nacional de Conservacion and Restauration has produced a manual "Cartilla Patrimonio en Tierra" which provides basic concepts on performance of adobe vernacular buildings and advise on use for ensuring safety in the aftermath iof a seismic event, for damaged buildings. A more comprehensive and technically oriented publication has been prepared by the Fundación Altipiano for the "Plan the Recuperación de Patrimonio de Arquitectura Tradicional en Tierra" for the O'Higgins region, to be implemented in the period 2010-2012. The booklet classifies the different type of traditional earth constructions and their structural performance and identifies the methodology for conservation and repair, following the general international guidelines according to ICOMOS. It then provides a set of criteria to evaluate type and level of damage and correlate this to possible inherent construction defects or previous deficient interventions. Finally outlines both traditional repairs method and novel strengthening techniques. Given the lack of technical research and development in this field in Chile, extensive reference is made to activity carried out in Peru' by the Universidad Catolica Pontificia de Lima.

8.4 Modern Buildings

Modern buildings appear to have behaved well in the earthquake throughout most of Chile, with notable exceptions discussed in the previous sections. For modern construction more than historical construction, the actual level of ground shaking is of particular interest, and preliminary evidence discussed in Section 2.2 suggests that ground motion levels were in excess of code level in some areas. This suggests that the overall performance of modern buildings was compatible with (or in excess of) the code intent of "life safe" performance under the design earthquake ground motion. We may also expect that the very large duration of strong ground shaking is compatible with the heavy damage to degrading historical and vernacular structures, but low damage to modern construction. These conclusions will need to be revisited as more accelerograms become publically available, particularly those recorded in the heavily hit areas of Talca, Concepción and Constitución.

The main lessons learned from the performance of modern structures were:

- Non-structural and architectural features need to be able to accommodate seismic movements, or life safe performance can be compromised. This was particularly clear from the Talca Court of Appeals building where a slender architectural beam which appeared to have very little reinforcement failed, which could have led to injury or loss of life had the building been occupied.
- A number of reinforced concrete shear walls failed due to buckling of reinforcement in the "boundary zones" at the ends of the walls. A large amount of confinement is required in these areas where compression strains can be very high.
- Several modern apartment buildings that seemed to have been in the direct path of the tsunami performed well, although there was scour at the foundations observed.
- Seeing that modern buildings generally performed well over much of Chile, many residents of buildings that did not perform so well were angry and demanding to be relocated to "safer" buildings. In some cases, such as the apartment buildings in Maipú, Santiago, all constructed by the same contractor, this appeared justified. In other cases, such as the Edificio Amalfi, the reluctance of tenants to return to apartments with apparently superficial damage was a concern for the building management.
- Similarly, when there is such a contrast between the performance of engineered and non-engineered construction, building owners and occupiers can be made to feel proud of having spent a little extra in the initial construction. Whilst it is clearly important to invest in culturally appropriate technologies in reconstruction efforts, in a modern but extremely seismic country such as Chile, all effort should be made to ensure that modern earthquake engineering principles are applied.

Chile's industry was heavily affected by the earthquake. The team visited a winery and a wood pulp plant in the Maule region, as well as observing silo damage scattered throughout the country. According to the representative of the winery, the wine industry overall lost 15% of all production – fortunately much lower than it could have been if the earthquake had occurred following the year's harvest. The winery we visited did not experience problems with water being contaminated by spilt wine, due to the modern cleaning system, but other wineries were affected.

The Arauco pulp plant in Constitución was still closed when we visited, and it is expected to be 3-4 months before they can reopen the plant. Just prior to our visit, it had been reported that Arauco would be reopening their Valdivia pulp plant, and that they had already restarted operations at most of its saw mills, more than half of its wood panel production plans and two power plants (http://www.businessweek.com/news/2010-03-19/arauco-to-restart-valdivia-pulp-plant-first-la-tercera-says.html). The local economy of Constitución, which is dominated by the pulp plant, will be heavily impacted, especially given the large clean-up and rebuild effort that is required there.

8.5 Infrastructure

This earthquake caused extensive damage to roads and bridges over a very large area. In general it was older bridges (such as the Puente Viejo Bridge in Concepción) that faired worst in this earthquake. The more modern bridges generally performed well showing that the codes are producing adequate designs based on the design earthquake ground motions. Where recently build bridges did fail it appeared to be related to poor ground conditions rather than poor structural design.

Numerous minor bridges were damaged restricting travel throughout the affected region but the damage to bridges along route 5, the main north-south highway could have had a much more profound impact on the country. However, by the time the team visited, many of the bridges were being repaired and even where damage had been catastrophic, with bridges collapsing completely, the main road often remained usable because each of the two carriageways ran on a separate bridge. The extra bridges were built as a result of road widening in 1994 rather than being specifically added to improve earthquake resilience, but this redundancy had meant that route 5 had remained open as traffic could be rerouted via the remaining intact bridges. While deliberately building this type of redundancy into a road network for earthquake protection could be challenging it should certainly be considered as an option when upgrading critical road links.

8.6 Social and Economic Impact

Chilean society has vast experience in earthquakes, but this will always be a traumatic experience and even a worse situation if a tsunami strikes the coast. Local knowledge about these phenomena's saved hundreds or even thousands of people, given the deficiency in the tsunami alert systems. Public and private communication systems in the south failed making impossible to know what was happening. The lack of electricity and water supplies added to the people's hysteria and the impression of an apocalyptic event generated a social chaos in the southern part of the country. People started to steal from supermarkets and local stores in order to supply themselves with food and water. This generated a shortage of supplies the second day after the earthquake. These actions were more critical in Concepción, where, vandalism acts and looting damaged the entire city centre and included looting private houses, stealing cars and also burning some large stores. People had to protect their houses with weapons as the city appeared to be at war. Two days after the earthquake government sent a military contingent to control the situation, imposing a curfew and leaving only 6 hours in the day for free transit in the streets. The frustration and a feeling of abandonment of the population was heightened by the government's delay in sending basic supplies and water, whihch reached only the fourth day after the main shock.

Many modest fishing towns were destroyed by the tsunami, affecting one of the poorest sectors of the country, the majority living in camping and concerned by their situation for the winter starting in the next couple of months.

Other important social impact has been in several communities in Region del Maule. Many little towns lived of tourism, with historic and cultural heritage buildings, churches and houses. Almost the

50% of theses constructions were destroyed, leaving many families homeless and without their main economic source.

The new government leaded by the multimillionaire Sebastian Piñera promised to the population the reconstruction of about 13.994 houses and subsidy the reparation of 61.956 houses. Many people feel that the temporary houses constructed in some towns will be the final solution for the people.

Figure 8-6: Talcahuano Port after the earthquake

According to a report given by Chile's government the amount of losses from the earthquake are US$30.000 millions of dollars, which US$21.000 millions correspond to infrastructure losses, and US$1.000 millions are related to emergency supplies and rubbish removal. The losses in houses ascend to US$3.700 millions; health in US$2.773 millions and education US$3.015 millions. The number of homeless people is approximately 800.000, 2 millions of affected people and 25 severely damaged hospitals. One of the most affected areas is industrial and artisanal fishing, Ports in the VIII Region, retail stores and wind industry. The VIII region is an industrial area of Chile, where the most important industries where affected by the earthquake and tsunami: Iron and Steel Company Huachipato S.A. and Ship Building & Ship Repair ASMAR S.A., both of them in Talcahuano city. These two companies are closed leaving thousands of people unemployed until their complete reparation.

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