

## THE M8.8 CHILE EARTHQUAKE, 27 FEBRUARY 2010

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### SUMMARY

The largest earthquake of 2010 by magnitude ( $M_w$ 8.8), and the subject of this article, struck south-central Chile in the early hours of 27 February 2010. The earthquake was a “mega-thrust” event, involving the rupture of a section of the Nazca-South American plate boundary, where the Nazca plate dips at a shallow angle beneath the Pacific margin of South America.

Understanding this event and its effects, including tsunami is of particular significance to urban centres that share close proximity to “subduction zones”. These include Seattle, Vancouver, Tokyo and Wellington, together with smaller New Zealand towns of the eastern North Island and upper South Island. The tectonic setting of south-central Chile has similarities to the East Coast of the North Island, and the modern built environment of Chile shares attributes with New Zealand. However, New Zealand has not experienced a large subduction earthquake in the North Island region in at least 200 years, so an understanding of the Chile event and its impact is important for bench-marking of local practices and building resilience.

This report summarises the observations of the NZSEE/EQC teams, supplemented by media updates on the Chilean reconstruction experience one year after the earthquake.

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## 1. INTRODUCTION

Worldwide, in the year 2010, there were 22 earthquakes of magnitude 7 or greater, this being the largest annual total recorded since 1968. In terms of societal impact it was also a year of contrasts. A shallow earthquake of magnitude 7.0, near the Haitian capital, Port-au-Prince on 12 January claimed more than 300,000 lives and displaced perhaps more than 1 million inhabitants<sup>14</sup>. In New Zealand, seven months later, the Darfield, Canterbury earthquake of a similar size caused the largest insured loss to property in this country's history, but no deaths. The largest earthquake of the year by magnitude ( $M_w$ 8.8), and the subject of this article, struck south-central Chile in the early hours of 27 February 2010. The earthquake was a "mega-thrust" event, involving the rupture of a section of the Nazca-South American plate boundary, where the Nazca plate dips at a shallow angle beneath the Pacific margin of South America.

The tectonic convergence rate of the Nazca-South America plate boundary at this latitude (70 mm/year) is almost twice that of the Hikurangi margin, New Zealand. The effects of repeated large earthquakes and tsunamis are woven into the mythology of the indigenous Mapuches and documented by the Spanish every few decades since their settlement of the region in the 1500s (Cisternas *et al.* 2005; Museo Histórico Nacional de Chile, 2009). Although recently surpassed in size by the Tohoku, Japan earthquake of 11 March 2011, the Chile earthquake of 2010 remains the sixth largest ever recorded<sup>15</sup> and was the first of its type to test buildings constructed to modern standards.

Understanding this event and its effects, including tsunami is of particular significance to urban centres that share close proximity to "subduction zones". These include Seattle, Vancouver, Tokyo and Wellington, together with smaller New Zealand towns of the eastern North Island and upper South Island. The tectonic setting of south-central Chile has similarities to the East Coast of the North Island and Hikurangi trench, and the modern built environment of Chile shares many attributes comparable to that of New Zealand.

On 24 April, three members of a New Zealand Society for Earthquake Engineering mission flew to Chile under the leadership of Peter Smith, with the main 12-member team under Hugh Cowan following one week later. The team members covered a wide range of disciplines that included emergency management, landscape architecture, geophysics, civil, structural and power transmission engineering. The mission purpose was to gather data on the earthquake and its impact on the performance of systems, buildings and infrastructure relevant to New Zealand with a particular focus on identifying potential vulnerabilities in disaster risk management arrangements and priorities for the early stages of disaster recovery planning.

A significant aspect of the mission was the willingness of Chilean authorities and experts to meet with the team and discuss areas of interest for New Zealand. To a large extent this cooperation is due to the efforts of Claudio Oyarzo-Vera and Patricio Quintana-Gallo who are Chilean earthquake engineering doctoral students at the Universities of Auckland and Canterbury, respectively, and who are Society members. One of us (H. Cowan) visited again in late August-early

September, accompanied by Earthquake Commission insurance manager, Lance Dixon, to study the insurance sector response and recovery. This visit, which coincided with the beginning of the Canterbury earthquake sequence (4 September) involved meetings with loss adjusting firms, reinsurance and insurance companies and banks, as well as additional field inspections of tsunami and earthquake damage in the region surrounding Concepción.

During the visits to Chile, the teams were able to visit affected areas around Concepción and along the adjacent coast where a tsunami devastated a number of communities. Time was also spent in Valparaíso to the north and the capital, Santiago, to discuss topics of interest with engineering practitioners, academics and government officials. With financial support from the Earthquake Commission, the Department of Building and Housing, Ministry of Civil Defence and Emergency Management, Transpower, Victoria University of Wellington, Australian Earthquake Engineering Society and team member employers, the Society initiated and managed the mission.

This report summarises the observations of the NZSEE/EQC teams, supplemented by recent media updates on the Chilean reconstruction experience. Completion of the report was delayed by the 2010-2011 Canterbury earthquake sequence and the competing demands on team members and sponsoring organisations. A number of publications about the 2010 Chile earthquake have since appeared from other sources, and the reader is encouraged to refer to EERI (2010) for a summary of physical impacts, as at June 2010, and Rios (2011) for a description of the response of the Chilean insurance market.

## 2. THE 27 FEBRUARY 2010 CHILE EARTHQUAKE AND TSUNAMI

### 2.1 The Earthquake

On Saturday, 27 February 2010 at 0334 hours local time, a magnitude  $M_w$  8.8 earthquake struck the central south region of Chile, with its epicentre at the coast in the region of Maule (Figure 2.1a). The earthquake was an inter-plate subduction event, along the boundary between the Nazca Plate and the South American Plate. The rupture initiated at a focal depth of about 35 km and extended in a north-south orientation over an area about 600 km long and 100 km wide (Figure 2.1b). Warping of the ocean floor resulted in a destructive tsunami that swept into several coastal settlements, including the naval base and shipyard near Concepción.

The rupture duration was more than 140 seconds (Figure 2.1c) with ground shaking exceeding 0.05g in some areas for more than two minutes and a maximum acceleration of 0.65g recorded at one site in Concepción (R. Boroschek, University of Chile, pers. comm.). More than 12 million people or 72% of the national population experienced intensity VII or stronger shaking, with 521 deaths reported overall. The damage to housing and infrastructure included about 200,000 dwellings damaged or destroyed including a number of multi-storey buildings (EERI, 2010), greatly surpassing in economic terms the losses caused by the 1960 Valdivia earthquake of magnitude 9.6 – the largest ever recorded world-wide – and the 1985 Valparaíso earthquake of magnitude 7.7 (Rios, 2011).

<sup>14</sup> <http://www.usgs.gov/newsroom/article.asp?ID=2679>

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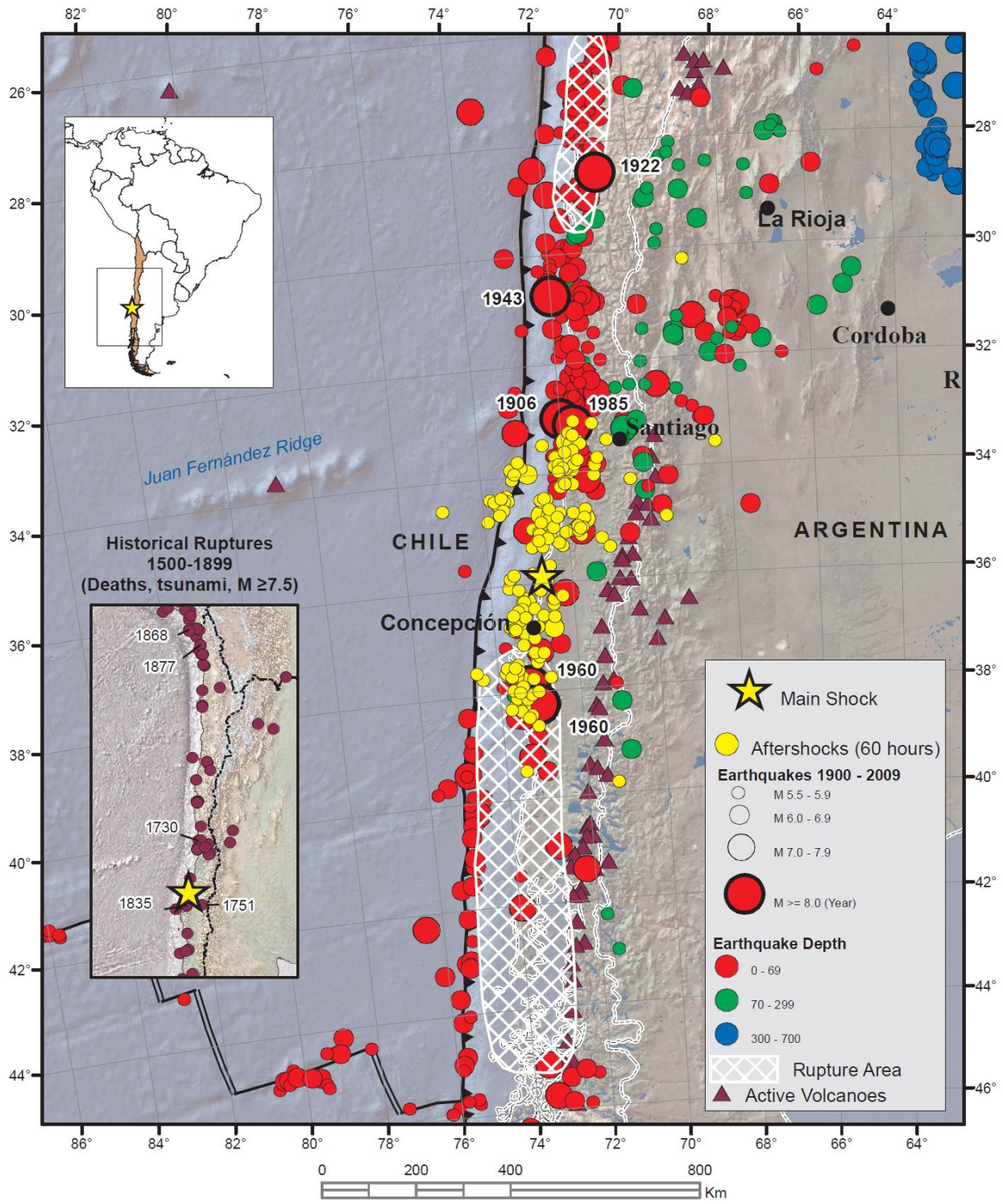
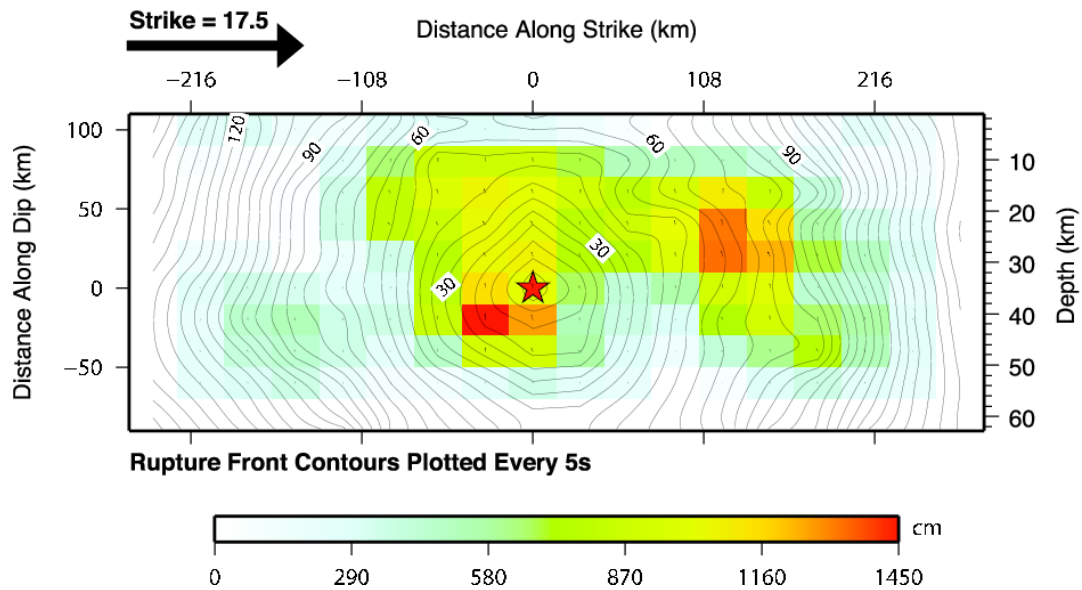
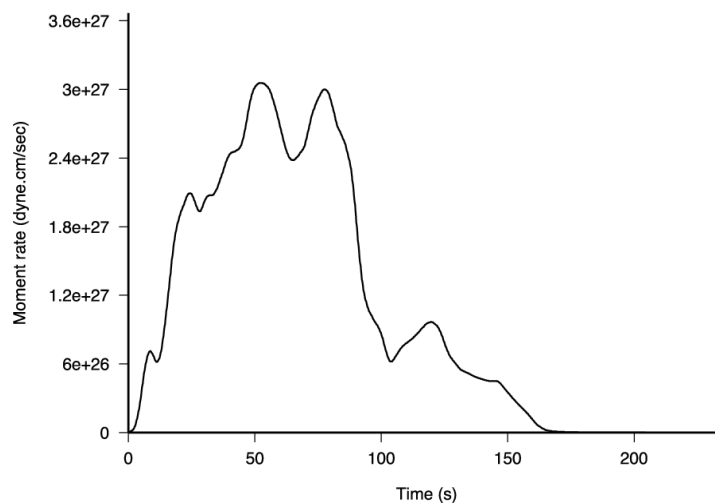


Figure 2.1a: Map of central Chile showing the rupture area of the 2010 earthquake (yellow symbols) in relation to earlier historical earthquakes. Source: USGS.



**Figure 2.1b:** A model of the fault rupture and a source-time function for the Feb 27, 2010 Mw 8.8 Maule, Chile earthquake produced from distant broadband seismograms by matching measured and computed waveforms. The model depicts a view looking down on a dipping inter-plate fault plane. The horizontal axis gives distance from the hypocentre (red star) parallel to the coast (north to right, south to left), a total of about 500 km. The vertical axes give distance along dip from the hypocentre (left axis) or alternatively depth (right axis). Contours give the time in seconds of the rupture front as it propagated, while the colours give the fault displacement in cm (maximum 7.5 metres). Source: Gavin Hayes, National Earthquake Information Center (NEIC) of United States Geological Survey 2010.



**Figure 2.1c:** The rate of moment release plotted against time after the earthquake mainshock origin. Source: Gavin Hayes, National Earthquake Information Center (NEIC) of United States Geological Survey 2010.

## 2.2 The Tsunami

The tsunami generated by the 27 February 2010 earthquake swept into a number of communities along the Chile coastline, with initial waves arriving within 30 minutes, but subsequent and larger surges of up to 3-4 metres arriving between 90 minutes and four hours after the earthquake (EERI, 2010). The trans-Pacific tsunami took about 13 hours to reach New Zealand, where warnings were issued by the Ministry of Civil Defence and locally strong currents and surges of about half to one metre amplitude were recorded, around Chatham Islands and at several locations along the eastern coasts of the New Zealand (Figure 2.2a, Pearse, 2010).

The team visited severely affected resort communities in Chile, 40 km north of Concepción, (Dichato and El Pingueral) and the commercial port area of Talcahuano. The effects of the tsunami were variable along the coast, with bays open to the north most severely affected and inundated to depths of several metres for hundreds of metres inland (Figures 2.2b, 2.2c). As observed in previous events elsewhere (e.g. Bell *et al.*, 2005), the nature of the damage ranged from scouring of shallow foundations and bridge piers during both inundation and drawdown, to hydrodynamic and impact loading of structures (2.2d).

Uplift and landward transport of boats was commonplace, with in some cases large vessels washed ashore with tonnes of debris mixed with marine sediment (Figure 2.2e). The debris

and saltwater contamination has posed a significant challenge for the clean-up and restoration of basic services and several

of the affected residential areas had barely begun to recover by the first anniversary of the disaster (Ramirez *et al.*, 2011).



*Figure 2.2a: Strong currents from the Chilean tsunami move under the Westshore bridge, Napier (from Pearse, 2010).*



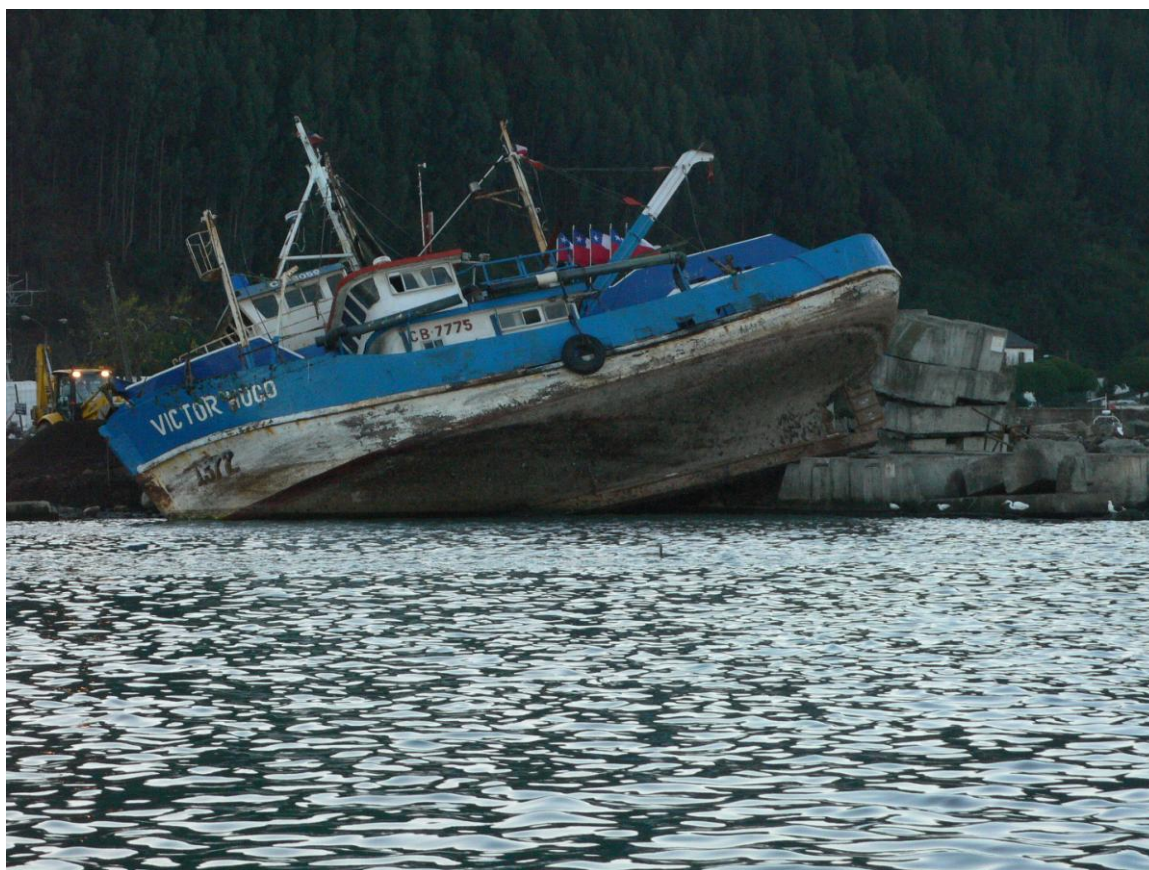
*Figure 2.2b: Tsunami fill-depth of ~2 m in homes at the coastal resort of El Pingueral, north of Concepción. (Photo: Hugh Cowan).*



*Figure 2.2c: Complete destruction of coastal dwellings where the tsunami came ashore at Dichato, north of Concepción. (Photo: Katherine Hill).*



*Figure 2.2d: Receding water caused severe scouring of foundations beneath coastal structures at Dichato. (Photo: Hugh Cowan).*



*Figure 2.2e: The tsunami carried many vessels ashore, severely impacting local maritime transport and trade. (Photo: Graeme Beattie).*

### 3. EMERGENCY READINESS AND RESPONSE

#### 3.1 Readiness

Chile has experienced many damaging earthquakes and tsunamis in its history and as a consequence it was expected that there would be a correspondingly high level of awareness and readiness at most levels. In New Zealand this is accomplished by having in place a national strategy for civil defence emergency management, and legislation and procedures that acknowledge and manage the hazard risks faced by communities, infrastructure and the economy. The goal of the New Zealand national strategy is to generate resilient communities, described as communities that understand and manage their hazards. In our setting, resilience will be achieved through reducing risks, enhancing readiness, having a response mechanism in place and the ability to implement recovery strategies once a disaster has occurred. The approach used in New Zealand devolves many of these responsibilities to local government authorities for implementation facilitated, co-ordinated and supported by central government agencies and the private/commercial sector.

Despite the high earthquake hazard faced by Chile it appears that the hazard research base is hampered by the lack of an integrated seismic and geodetic monitoring network resulting in poor records of seismic events, with only a scattering of

recordings for the 2010 earthquake and few of those available for analysis in the public domain. This is a deficiency that New Zealand experienced until a decade ago, but fortunately no longer faces given the coverage provided by GeoNet<sup>16</sup>. Such data are critical to monitoring changes in the environment and in the case of GeoNet, the contractual model for the design and operation of the facility and its accounting treatment underpin a commitment to stewardship of national capabilities. A policy of open data sharing also stimulates innovative research on seismic hazard. This in turn allows for adaptations in the built and the social environments to better cope with the likely impacts. With the recent creation of a natural hazards research “platform”, the New Zealand environment reflects an improving climate of collaboration and co-ordination of effort<sup>17</sup>, which allows results to be used to enhance risk reduction and improve readiness.

It appeared that Chile operates a similar structure as New Zealand for emergency response, with ONEMI the government agency that manages the national emergency response and local government expected to provide the initial response in its communities. However, it was unclear if Chile

<sup>16</sup> [www.geonet.org.nz](http://www.geonet.org.nz)

<sup>17</sup> <http://www.naturalhazards.org.nz/>

uses a national strategy for comprehensive emergency management to co-ordinate and promote, risk reduction and readiness as well as response and recovery functions. ONEMI officials indicated they had implemented a national public awareness programme for readiness, including a schools programme but there were some indications that communities and households could have been better prepared for the impact of an earthquake.

Preparedness for tsunamis seemed to be well developed in the “at risk” coastal communities where there was high awareness of the risk posed by local source tsunami and the “go inland and get to high ground” doctrine was well understood and was applied in this event. The good response by residents of coastal communities to the tsunami threat was marred by the response provided by central authorities in Santiago, which involved issuing and then cancelling a warning but without adequate means to disseminate or receive relevant information from affected areas. Reforms implemented since last year have reportedly addressed technical communication deficiencies between the responsible central agencies - ONEMI, the Hydrographic and Oceanographic Service of the Navy (SHOA), the Institute of Seismology of the University of Chile and the armed forces – but the resourcing and training of regional municipal authorities to respond effectively to tsunami remains in doubt (Astorga, 2011).

### 3.2 Response

As witnessed of the M7.1 Darfield, Canterbury earthquake of 4 September, the occurrence of the 2010 Chile earthquake in the very early morning minimised impacts on people. The study team was not able to gain a clear picture of how the emergency management authorities responded at national, regional or local levels. The team visited areas devastated by the tsunami at Dichato and Talcahuano and from the media was aware of the inquiry into the management of tsunami warnings by the Chilean Navy, but there was no contact with municipal emergency management authorities outside Santiago. Contact with ONEMI to discuss their role in the response was brief.

Some of the lifeline utilities evidently responded to the earthquake very well. The commercial company providing potable water and sewerage in Concepción responded well and the operators of the Santiago international airport were able to resume flying operations quickly. There were indications that mobile telephone services and electricity generation were restored quickly although reconnecting and providing consumers with electricity was slow. Local gas distribution in Concepción was not restored fully at the time of the visit, nine weeks after the event.

The lifeline utilities that made better responses were judged to have completed sound planning and had conducted exercises and practices. In addition those utilities (and communities) that had in place pre-event, strong leadership and corporate cultures seemed to respond better. The water supply company admitted to not having a planned response, but due to the leadership and culture in the company, priorities and plans were quickly developed internally and implemented in Concepción, drawing on the willingness of staff to help and the company’s ability to move additional staff into the worst affected areas.

Continuity in some lifelines was aided by having some built-in redundancy and resilience. The port at Coronel uses base isolators in its container terminal and the facility withstood the impact of the earthquake. Many of the major highways are of multi-lanes and while bridging was damaged, the authorities

were able use other lanes and diversions to keep traffic flowing. Having seen the earthquake’s impacts on utilities some indicated they intended to now add redundancy and improve network resilience such as the installation of seismic shut-off valves in the water supply network.

The city of Concepción suffered a break-down in law and order immediately after the earthquake. Deteriorating security reportedly resulted in a vigilante approach being adopted in some communities and a wider deployment of armed Army units to patrol and control urban areas. It appeared that the looting was not caused by shortages of basic supplies or the inability to move supplies into the affected area. It seems the looting was opportunistic rather than driven by necessity. Using military units to provide security diverts resources from what could be urgent assistance tasks.

First-hand accounts reported to some of our team (Allan, Bryant and Davis) suggest that the open space network was used heavily for recovery during the emergency period. Most people had moved on by the time we arrived. Interviews with locals revealed that the period of occupation of these places ranged from a week to two months. Key factors determining the use of these areas appear to have been proximity to people’s homes, availability of water, community ties, elevated land, prior use in other emergencies, and security. We were told that the urban lagoons and parks have traditionally been important places for communities to shelter after an earthquake. This is possibly because both have access to elevated land and to water.

Linear parks seem to be common in Chilean cities and towns (Talca, Santiago, Concepción) and appear to have been used to good effect for shelter during the emergency period. Linear parks have the benefit of maximum interface and often knit two distinct urban types together (e.g., urban/sub-urban), thus serving a wider catchment than a typical neighbourhood park which is more insular and centralized.

During the recovery period, open space can help to resolve the potential conflicts between short-term and long-term recovery strategies by ‘buying time’. This was clearly in evidence in Talcahuano, Concepción and Constitución. Urban plazas and streets were used to support markets and temporary buildings, e.g., tents and containers for essential services, supermarkets, banks, and hardware. Larger open spaces (e.g., sports fields) were used for the storage of debris, building materials and for the provision of schools and emergency housing (Constitución). Medical services were set up in tents on open ground.

Open spaces in New Zealand centres similarly will offer amenity in emergencies and in the aftermath of major disasters – as now occurring in Christchurch with Hagley Park becoming a central hub for large scale civic events while the central business district remains closed for demolition and repair.

Schools were relocated in tents, community halls, modular structures, adapted buses, etc. A timeline of 2 months was given to the education minister by the President to complete this task (100% of the students back to school). That was accomplished the day the team arrived in Chile.

## 4. RECOVERY

The team saw examples where having plans for disposing of debris quickened the authorities’ abilities to clear roads and get communities and the economy operating again. Similarly, having contingency plans to adjust environmental

management standards temporarily (such as discharge of untreated waste water) aids community recovery. The production and deployment of temporary housing in the

Concepción area was increased significantly by the use of existing plans and capacities (Figure 4.1a).



**Figure 4.1a:** *Increased demand for temporary housing following the earthquake and tsunami was met largely through existing capacity for low cost social housing. Fr Julio Stragier (right) here demonstrates to Hugh Cowan, an example of the standard, 18 m<sup>2</sup> unit produced for the charity “Un Techo Para Cristo” (A Roof for Christ) at his yard near Coronel, south of Concepción. Similar units were built by the charity “Un Techo Para Chile” (A Roof for Chile) based in Santiago. (Photo: Katherine Hill).*

A post-earthquake, psychosocial survey of ~22,000 households carried out during May and June 2010, identified significant regional variations in the severity of impacts that correlate with the pre-earthquake quality of housing, employment skill-levels and income (Larrañaga and Herrera, 2011). In the three worst affected regions approximately 17% of homes were destroyed or seriously damaged, and analysis

of all regions in which the earthquake (including tsunami) caused damage to housing indicates that the abundance of the poorest quintile of the population rendered homeless is three times that of the richest quintile.

No matter how good the pre-event planning or the speed of the response and recovery, there will always be a need to manage

the public's expectations irrespective of the practicalities involved. The team encountered numerous residents who expressed dissatisfaction with the quantity and quality of information with which to adjust their lives and livelihoods. Despite cultural differences and expectations of entitlement, similar sentiments have been aired in New Zealand concerning the pace and direction of the Canterbury recovery to housing and commerce.

#### 4.1 Risk Financing

A key difference between New Zealand and Chile is the limited scope of financial protection for the population in Chile, because there is no compulsory insurance for natural disaster nor are there government catastrophe funds or other mechanisms to finance disaster risk (Rios, 2011). Insurance penetration is still low in Chile, with only 2-4% of homeowners voluntarily purchasing earthquake cover and a further 22% insured compulsorily for mortgage protection. Small to medium commercial enterprises exhibit low levels of insurance contracting, whereas large industrial firms and other publicly listed entities tend to have a higher level of protection. Risk financing for public infrastructure is clearly differentiated between concession-infrastructure for which insurance is required by law, and the wholly Government-owned infrastructure, including hospitals, schools and older highways that have low levels of cover. The majority of earthquake risks are reinsured abroad – either ceded to the headquarters of those foreign companies domiciled in Chile, or placed directly with large international reinsurers.

Despite the relatively low insurance coverage in Chile the 2010 earthquake nevertheless generated 221,000 claims with 189,000 claims corresponding to housing, with several hundred thousand additional uninsured families requiring government assistance due to the loss of their home, employment or both. At the time of our visits, private insurers' were cash settling all claims and the Government was still working out the parameters and delivery of welfare entitlements, so it was difficult to assess the efficacy of the actual reconstruction process as distinct from its financing.

#### 4.2 Displaced Population

A sense of community is crucial for fostering adaptation and learning from a disaster (Adger *et al.*, 2005; Miller, 2005). The Chilean earthquake suggested that communities will manipulate and use their local environment to encourage effective communication and support networks. Planners and designers can provide local environments that support this tendency, for example, local parks that include access to water, shelter, cooking facilities, etc. We saw evidence of whole communities being relocated because of complete devastation due to the effects of the tsunami. The Chilean government and the military established an emergency settlement several kilometres from the coastal village of Dichato (Figure 4.2a) with care taken to create amenity and to encourage a ready-made sense of community by allowing people to choose their neighbours.

Another way to encourage communities in emergency settlements is through urban structure—or the way a settlement is laid out. The military used a familiar Chilean urban structure to set out the emergency housing units and public spaces of streets and squares with communal facilities (washing, and child-care). The layout included short streets surrounding a public square, with 50 to 80 houses around a 110 x 60 m square. There were experiments in the way houses were configured to explore optimal relationships with respect

to environment and community. There was also evidence of people adapting their houses to suit their needs, e.g., adding back decks and other additions.

We were informed that the camps were to be occupied for no more than two years and community leaders and camp residents alike expressed confidence in the approach being taken. However, when we visited again in September more of those interviewed expressed concern about the rising incidence of alcohol and drug-abuse, domestic violence and other anti-social behaviours, with the problems variously attributed to a breakdown of social cohesion, unemployment and an emerging dependence on charity.

Non-governmental organisations including the "Challenge: Let's get back on our feet, Chile"<sup>18</sup> led by businessman and philanthropist, Felipe Cubillos<sup>19</sup>, are raising donations for repairs to schools and industry-training centers, particularly in the hard-hit fishing communities. One year after the earthquake, their targeted assistance has been described as effective, whereas the government-led housing reconstruction process is described by some commentators as deficient, with only half of the 127,000 household subsidies so far approved actually paid out, and only a few thousand homes rebuilt (Rebolledo, 2011). More than 200,000 families are still waiting to repair their home and four thousand families remain in the 106 temporary camps dubbed "solidarity villages". Recently, more radical demonstrations were originated in several villages near Dichato asking the central and regional authorities for prompt definitive housing solutions (Navarro, 2011).

#### 4.3 Economic Loss and Recovery

In broad economic terms, however, despite severe regional damage inflicted on fishing, forest industries and wine in particular, the Chile national economy has proven quite resilient thanks to record high copper prices. So although national output fell by 2.2% in March 2010, due to a ~18% drop in industrial production, and growth expectations for the year fell to 4.5%, only two months after the earthquake, the economy began expanding again and it is estimated that 2010 closed with GDP growth of 5.3% (Lefin, 2011). A US\$1.2 billion withdrawal from the Chile sovereign wealth fund (Copper Reserve) has been approved to finance the reconstruction of infrastructure, facilities, buildings and equipment, but progress on the ground is slower than earlier anticipated.

A total funding requirement for reconstruction of US\$8 billion has been estimated and the following breakdown recently published is illustrative: 6,168 repaired educational facilities, 133 hospitals (4,249 beds and 167 wards), 211 bridges, 1,554 kilometers of roads ; nine airports or airfields; 748 rural water systems, 41 dams, rain water collection and irrigation channels, 26 fishing coves, rebuild and repair homes destroyed 81,444 - other 288,607 (220 thousand subsidies, half of them to fund repairs). The figures indicate the scale of the challenge but not its complexities. For example, repairs to roads and

<sup>18</sup> <http://www.desafiolevantemoschile.cl/help-us-rebuild-chile/>

<sup>19</sup> Felipe Cubillos was among the 21 passengers and crew of a Chilean Air Force plane that went down with the loss of all lives off the Juan Fernández Islands, 830 km off the Chilean coast on 2 September 2011. The flight was destined for an official ceremony to celebrate the completion of reconstruction work following the 2010 earthquake and tsunami.

other public-private infrastructure is reportedly proceeding swiftly, but there is growing public skepticism of the recovery to residential housing with complaints that the government's communications policy has focused on highlighting the achievement of subsidies paid, rather than the dwellings repaired or rebuilt. It is noted that although the delivery of

subsidies and insurance settlements has been relatively efficient, the indemnities are not sufficient to repair all damage and the reconstruction process would benefit from stronger public-private sector coordination (Rebolledo, 2011, Ramirez *et. al.*, 2011).



*Figure 4.2a: An emergency settlement for those displaced by the tsunami, near the coastal village of Dichato. (Photo: Graeme Beattie).*

## 5. PERFORMANCE OF BUILDINGS AND RELATED STRUCTURES

### 5.1 Individual Dwellings

While there is a predominance of multi-storey apartment and commercial buildings in the major cities of Chile, some incorporating advanced seismic energy dissipation systems there are still many low-rise, stand-alone, single-family dwellings (see Figure 5.1a). Our contacts informed us that (in central-south Chile) the predominant means of construction of house structures traditionally has been either adobe and, confined masonry. Confined masonry is a system of lightly reinforced concrete columns and beams with an infill of masonry blocks and has been used in Chile since the 1930s. Generally, the columns and beams are cast after the blocks have been laid, and the first floor is also constructed of reinforced concrete, effectively distributing forces to the lower storey walls.

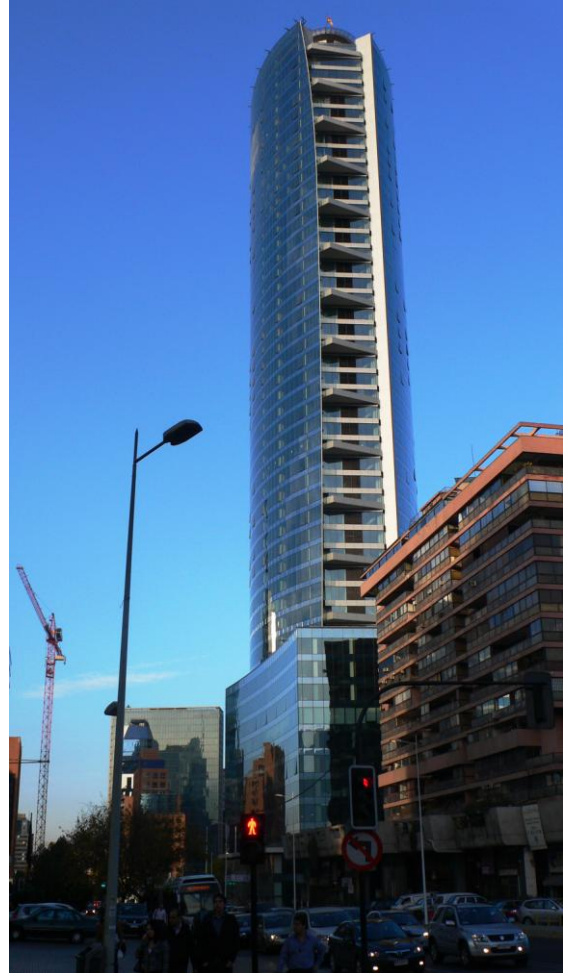
In recent years there has been an increase in the number of timber-framed houses and light steel-framed houses. Indeed, while the team was in Santiago we attended a reception at the residence of the New Zealand Ambassador, where a presentation was made to local invited guests by Framacad Solutions Ltd, a light-gauge steel building design company from Auckland.

Staff at Corporacion Chilena de la Madera (Corma), an organization that represents the private forestry sector remarked that many people are cautious about using light materials, because there is a perception that such materials are less durable and safe and have therefore attracted lower status compared to the various forms of masonry. Traditional adobe construction performs poorly in earthquakes and we were told (but did not see in areas we visited) that many of the 200,000 reportedly damaged houses would have been constructed with adobe blocks.

We did see examples of confined masonry, however, where subdivisions of identical houses with a confined masonry

lower storey and light steel frame upper storey were observed to have performed well (Figure 5.1b). Similarly good performance was observed in up-market suburbs with reinforced concrete lower storey homes and timber-frame upper storeys (Figure 5.1c). Several homes situated adjacent to a minor waterways on the alluvial floodplain nearby, however, suffered severe deformation as a result of localised lateral spreading beneath the floor slab (Figure 5.1d) comparable to

that seen widely in Canterbury at levels of shaking above approximately 0.2g. The difficulty with such comparisons, however, is that very few recordings of the actual ground motions are available from Chile.



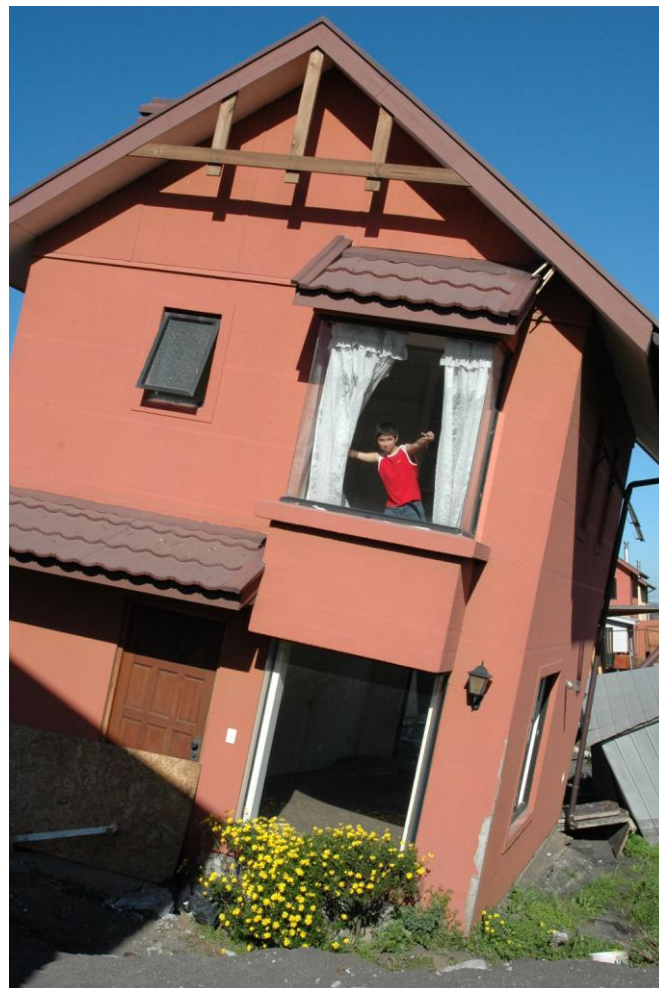
**Figure 5.1a:** *Modern structures in the business district of Santiago rival those anywhere for grace and sophistication. The “Titanium” tower in Santiago (right) is the tallest building in Chile (52 stories). This building incorporates locally-developed seismic damping technology, and is an example of progressive design capabilities. The residential family home (lower left) pictured in Valparaíso, would not look out of place in early 20th century Wellington. (Photos: Hugh Cowan and Graeme Beattie).*



**Figure 5.1b:** *A typical residential subdivision in the Concepción region where no sign of damage was observed. (Photo: Graeme Beattie).*



**Figure 5.1c:** Residential home in Concepción incorporating lower storey of reinforced masonry and upper storey of plywood and timber frame. (Photo: Hugh Cowan).



**Figure 5.1d:** Severe deformation of a concrete floor slab and settlement of a two-storey home, constructed on soft soils in an area that experienced lateral spreading adjacent to a waterway near Concepción. (Photo: Hugh Cowan).

At the time of our first visit in May 2010, a construction target of 20,000 temporary houses was nearly completed. All of these houses were being built using untreated timber, except

for the piles. A concern expressed by local advocates for timber design is that if people are required to live in these houses for longer than the advised two-year maximum period,

then houses may begin to deteriorate and the good earthquake performance of timber framing will be overshadowed by experience of poor durability.

Similar to New Zealand, Chile has a strong export market for sawn timber, particularly to China. This has driven up the local prices, making it more difficult to convince the Chilean public of the benefits of the lighter and more ductile light timber- or steel-framed structure. We were told that there was very little mechanization in timber-framed house building. There are no pre-nailing and truss plants, and construction on site starts with individual boards rather than delivered frames.

It would appear that New Zealand has better control of residential construction than Chile because most dwellings are covered by a non-specific design Standard (i.e., NZS 3604 or NZS 4229). All such construction in Chile is undertaken by specific design, which means that much of it is built without approval because there is no engineer reviewing and/or checking during construction or of the completed building.

The good performance in the Chile earthquake of modest dwellings framed in timber and light metal, with light roofs and wall cladding is consistent with the New Zealand (Canterbury) experience of homes on stiff, well-drained soils.

## 5.2 Historic buildings

The majority of buildings of historic significance are in the central city areas and include public assembly buildings, churches and early administrative buildings. Typically these buildings are of brick or lowly reinforced concrete construction. The facades are often heavily penetrated on the street façade (Figure 5.2a). Other walls to internal boundaries have few if any penetrations.

These buildings often suffered significant structural cracking, but few suffered collapse (Figure 5.2b).



*University of Chile, Santiago.*



*Damaged parapets to above.*



*Academia de Bellas Artes, Santiago.*



*Failed parapet Academia de Bellas Artes, Santiago.*

**Figure 5.2a: Damage to masonry parapets in Santiago. (Photos: Peter Smith).**

The Chileans appreciate the ornate building facades of the older buildings and an example of the structural support of such a facade during re-development of a site was identified during the mission. The examples that were identified appeared to be robustly detailed utilizing substantial

reinforced concrete columns anchored to the face of the basement excavations and integrated with the temporary retaining system for the excavation. The system performed well during the earthquake, preserving the façade in an undamaged condition.



*Temporary support of Building façade in central Santiago.*



*Temporary support of Building façade in central Santiago.*

**Figure 5.2b (Photos: Peter Smith).**

Repairs to buildings of a historic nature typically involved patch and repair techniques. There appeared to be no legislative requirements for retrofit of these buildings.

Due to a lack of legislative requirements for securing of what we would classify as earthquake risk buildings, parapets and other appendages were typically still present and were often damaged or failed during the earthquake. Fortunately the earthquake occurred in the early hours of the morning and the failures did not result in any significant loss of life.

Chile also has many 1930 to 1970 early reinforced concrete buildings, visually not too dissimilar to buildings of that age in New Zealand. These buildings generally performed well in the earthquake. The most extensive shear failure of spandrels in c1950 reinforced concrete buildings was found in the Ministerio de Relaciones Exteriores building in central Santiago (Figure 5.2c).



*Damaged spandrels to early reinforced concrete building in central Santiago.*



*Damaged spandrels to early reinforced concrete building in central Santiago.*

**Figure 5.2c (Photos; Peter Smith).**

Many of these buildings were also constructed without seismic separation and there was minor damage caused by pounding. Buildings that adjoined buildings of the same height with similar storey heights, suffered only minor harmful affects of pounding on the primary structure of the buildings.

There were some exceptions where differences in the height of buildings and offsets between floor levels resulted in pounding which was detrimental to the structure of one or both buildings (Figure 5.2d).



*Low rise commercial buildings in central Santiago.*



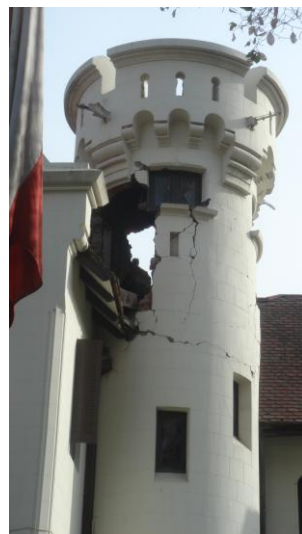
*Pounding between buildings in central Santiago.*



*Pounding between tower and podium of Direccion Regional Santiago Centro.*



*Pounding between tower and dwelling in Santiago.*



*Pounding between tower and dwelling in Santiago.*

*Figure 5.2d: Pounding between structures. (Photos: Peter Smith).*

The trip was sufficiently after the earthquake that some remedial works were already in progress (Figure 5.2e).



*Low-rise commercial building with shear failure of columns due to non-isolation of infill walls, Valparaíso.*

Steel K braces had been used to retrofit two three storey buildings at the University of Concepción (Figure 5.2f).



*Low-rise commercial building with shear failure of columns due to non-isolation of infill walls, Valparaíso.*

*Figure 5.2e (Photos: Peter Smith).*



*Steel K braced retrofitted to three-storey building at University of Concepción.*



*Unyielded steel active link in three-storey building at University of Concepción.*

*Figure 5.2f (Photos: Peter Smith).*

### 5.3 Apartment Buildings

In general, engineered buildings subjected to intensive earthquake motions in Chile performed well. The greatest damage in this earthquake was suffered by tall buildings built on deep saturated sediments. Similar structures built on dry soils or rock foundations appeared to have been largely unaffected.

The most significant damage occurred to medium to high-rise apartment buildings. Prior to the 1985 earthquake apartment buildings were typically under 15 storeys in height and had almost all apartment walls as thin reinforced concrete gravity and lateral load resisting elements. The satisfactory

performance of these buildings in the 1985 earthquake resulted in the industry extending this form of construction into taller buildings, typically up to 25 storeys in height.

For most engineered buildings, earthquake performance in New Zealand during a similar-sized earthquake should be similar to or better than that in Chile. The obvious difference in the construction of multi-level apartment buildings in Chile compared to New Zealand is the almost exclusive use in Chile of thin concrete shear walls, in conjunction with cast in-situ concrete floor slabs. There appears to be little use of beam-column frames, or precast concrete or steelwork, in

conjunction with the shear walls. Thus, from a New Zealand perspective, the structures we inspected looked very stiff, comparatively heavy and structurally inefficient. These buildings typically had reinforced concrete shear walls in each direction, often with structural discontinuities at the lower floor.

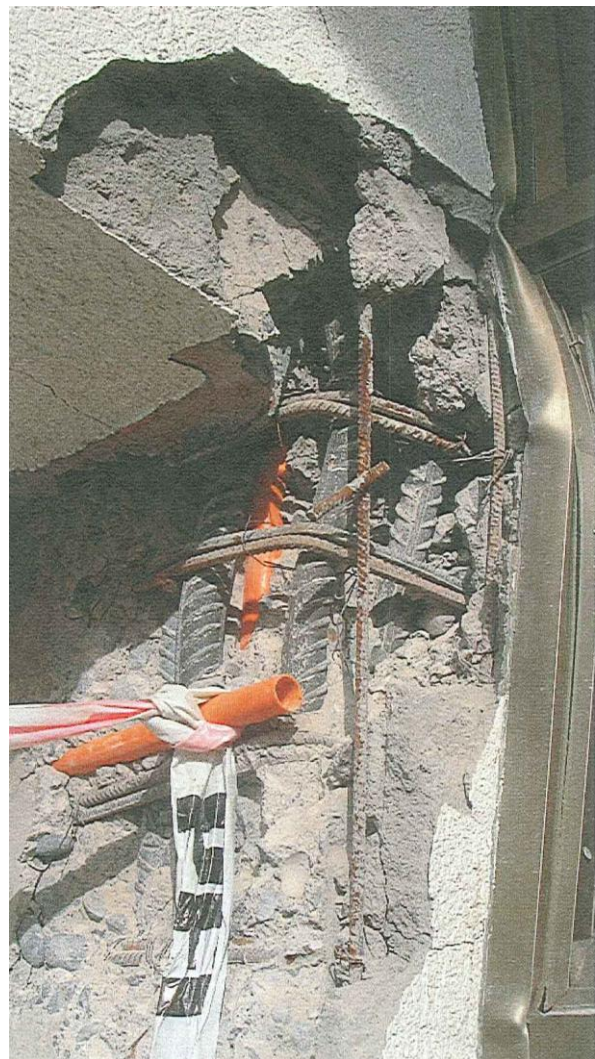
Detailing of these walls is understood to have been in accordance with pre 1995 ACI requirements. Typically the tension and compression reinforcement was inadequately confined and wall thicknesses of 200 mm were used for 16 storey and 250 mm were used for up to 25 storey buildings (Figure 5.3a).

These lightly reinforced walls were often constructed without the horizontal shear and confinement steel being anchored into the core.

These walls typically failed in flexure with horizontal cracking below first floor level. The failure mechanism demonstrated the potential for buckling of the vertical reinforcement to cause spalling of the cover concrete. With the cover concrete spalled and the compression reinforcement ineffective due to buckling, there was a significant reduction in the area of concrete left to resist the compression load and the concrete core remaining being unconfined, resulted in progressive failure of the remaining concrete core resulted in a vertical failure of the wall. Where the outer edge of transverse walls were supported on lightly reinforced columns, the significant load induced under overturning of the shear wall above resulted in column failure.



*Los Cerezos Apartment building in Santiago.*



*Lack of confinement to walls in Los Cerezos Apartment building.*

*Figure 5.3a (Photos: Peter Smith).*

The partial collapse of a modern commercial building, Torre O'Higgins in Concepción, resulted in prolonged evacuation of the entire surrounding block with consequences for economic

and social recovery, this being a very similar case to the Grand Chancellor tower in Christchurch (Figure 5.3b).



**Figure 5.3b:** *The partial collapse of large commercial buildings, such as the O'Higgins Tower of Concepción, Chile (left) and the Grand Chancellor Hotel of Christchurch, New Zealand (right) highlights the vulnerability of surrounding areas to prolonged denial of access and business interruption. (Photos: Hugh Cowan).*

A large number of multi-storey apartment buildings inspected in Chile had thin shear wall elements that suffered significant damage in the lower storeys. Flexural-compressive shear wall damage was commonly observed at the lower levels of multi-storey apartment buildings affected by the earthquake. In one case in Vina del Mar a shear wall had crushed and collapsed completely, leading to the portion of the building supporting it dropping over 600 mm (Figure 5.3c). In another spectacular case the use of columns with a low level of confinement under the outer edge of alternate shear walls led to the total overturning collapse of a 13-level apartment building in Concepción (Figure 5.3e). The principal reasons for the poor performance appeared to be the inadequate confinement of the

main vertical steel and the core concrete in relatively thin section lightly reinforced concrete shear walls..

Some effective emergency propping systems had been used to secure damaged buildings and prevent further damage until permanent repairs could be designed and implemented (Figure 5.3d).

The significance of the direction of the primary earthquake pulse relative to the plan orientation of building was evident in the Plaza Mayor apartment complex where a series of 5 essentially identical apartment buildings with different orientation suffered significantly variable damage (Figure 5.3f).



**Figure 5.3:** *(c - left) Collapse of a shear wall in a multi-storey apartment block in Viña del Mar. (d - right) Use of temporary props in another damaged apartment block. (Photo: Graeme Beattie).*



*Figure 5.3e: Catastrophic failure of the multi-storey “Alto Rio” apartment block in Concepción. (Photo: Hugh Cowan).*



*Damaged tower to Plaza Mayor building.*



*Damaged tower to Plaza Mayor building.*

*Figure 5.3f (Photos: Peter Smith).*

In some locations where shear wall or column failures had occurred, brittle fractures in flexural reinforcing steel were also evident (Figures 5.3g and h). These appeared to be linked to localised cyclic buckling and partial re-straightening of the reinforcing steel. This occurred where confining steel had

failed to fulfil its function of retaining the core concrete in place or where the tie spacing was perhaps too large relative to the diameter of the bar being confined. The long duration of strong cyclic ground motion in this earthquake may have been a factor in causing this mode of damage. With this in mind for

New Zealand application, the standard multi cycle loading regime, using cycles with increasing displacement should be reviewed to ensure that member degradation is being accurately assessed.

Significant damage occurred to apartment buildings, which lacked regularity of structural form, emphasising the importance of avoiding irregularity of structural form, especially in the lower floors of taller buildings. The challenges posed in providing car parking facilities in the lower floors of apartment buildings where the inter tenancy walls to the apartments are used as the structural system above the car parks creates excessive demand on the lower structural system.

In buildings with limited ductile walls in one direction and ductile reinforced concrete frames in the other direction, there must be some concern over the ability of ductile reinforced frames to restrain the upper portion of limited ductile walls over the lower portion of such walls. The steep failure plane of

the shear failure of the unconfined core concrete provides a perfect sliding interface for the upper portion of the wall to translate relative to the lower portion and thereby become unsupported leading to total collapse.

The ability of many substantial apartment buildings with shear walls in both directions to remain standing with the structural failures present in the primary structural walls highlighted the inherent resilience of these buildings against structural collapse. Many New Zealand buildings may not have such resilience and while the buildings may still be standing, they may not be able to be repaired.

The need for shear walls to be detailed to prevent buckling of tension and compression reinforcement in areas where inelastic deformations are expected and to confine the core concrete that must provide an essential part of the compression resisting structure was amply demonstrated in the structural failures in Chile (Figure 5.3i).



*Figure 5.3g and 5.3h: Fractured reinforcing steel in single storey reinforced concrete frame (left) and damaged shear wall (right). (Photos: Clark Hyland).*



*Figure 5.3i: Shear wall failures, Plaza del Rio, Concepción. (Photos: Peter Smith).*



*Shear wall failure, Plaza del Rio, Concepción.*



*Shear wall failure, Plaza del Rio Apartments, Concepción.*



*Apartment building, Santiago.*



*Failed shear wall in apartment building shown to the left, Santiago.*

*Figure 5.3j (Photos: Peter Smith).*

Many of the buildings incorporated LT or T shaped walls, which perform in an asymmetric manner under lateral loading with the steel in the T or L shaped leg rarely yielding while the tension at the end of the thin wall yielding in most cycles. This

action is thought to have resulted in high compression forces in the in-situ floors between walls, actions, which are not considered in the analysis of the building (Figures 5.3j and 5.3k).



*Figure 5.3k: Floor slab shear damage at end of shear walls in an apartment building in Concepción. (Photo: Clark Hyland).*

#### 5.4 Strengthening of buildings

While there were few buildings that had been retrofitted, the Festival Building in Valparaiso had been retrofitted following the 1985 earthquake. Strengthening consisted of in-situ thickening of the failed walls. Retrofitting consisted of casting

a thickening against damaged walls (Figure 5.4a). Where the construction could be identified the tie to the existing wall was nominal consisting of 6 mm pins at 200 mm c/s around the perimeter. The strengthening was inadequately pinned to the original construction and delaminated.



*Figure 5.4a: Shear wall delamination – Festival Apartment Building.  
(Photo: Peter Smith).*

#### 5.5 Commercial Buildings

Santiago has the most significant commercial centre that was exposed to severe earthquake shaking. The tallest building in Santiago is currently the Titanium Building at a height of 190 m. The building has a total of 130,000sq m of floor space in 7 basement levels and 52 stories above ground level. The Titanium Building is an elegant building of reinforced concrete construction with curved glazed facades.

The building is of advanced design incorporating energy dissipaters, which are activated by the cumulative inter-storey drift over every three floors above level 15. Large steel cross braces are used to transfer deformations to the dissipaters at the ends of the building in the transverse direction while secondary shear walls are used for this purpose in the longitudinal direction. The dissipaters induce yielding in multiple U plates to dissipate energy (Figure 5.5a).



*Titanium Building, Santiago.*



*Energy dissipaters Titanium Building, Santiago.*

*Figure 5.5a (Photos: Peter Smith).*

The building was designed using time-history analytical techniques and had a period of 4.4 sec in the longitudinal direction and 5.5 seconds in the transverse direction. The primary torsional period was 3.7 sec. The transverse dissipaters have a design load of 440 tonnes while the longitudinal dissipaters had a design load of 300 tonnes. Design drift was limited to 410 mm under earthquake.

The building has hollow core floors. The hollow core floor units are cast in a precasting yard and not extruded as they are in New Zealand. Despite the units being cast, no web reinforcement is incorporated in the units. The support details for the hollow core differ from current New Zealand practice as the top flange is removed in alternate cores and reinforcement introduced into these cores. The reinforcement



*Catholic University of Chile building.*

extending through support beams into the units on the other side of the beam.

The precast flooring units are cast integrally with the supporting beams and topping.

The building performed well in the recent earthquake with only minor damage to some hollow core floor units near the ends of the building in an upper floor.

Several important buildings are base isolated. The Catholic University building in Santiago suffered very minor damage and had a permanent deformation in the lead rubber bearings (Figure 5.5b).



*Permanent offset of lead rubber bearing Catholic University of Chile building.*

*Figure 5.5b (Photos: Peter Smith).*

Base isolation was also used for a medical centre in Valparaiso. Again the base isolation provided effective protection of the near new building. Unusually different depth bearings were used for a portion of the building. These bearings appeared to be of insufficient depth to absorb the displacements capacity of the main bearings and the permanent offset of the bearings was close to the failure deformation of the bearing.

Base isolation was also used for a major military hospital in Santiago.

Most commercial buildings in Santiago appeared to have suffered little or no structural damage indicating that the design and construction of commercial buildings were to a higher standard than that adopted for apartment buildings (Figure 5.5c).



*Figure 5.5c: Undamaged commercial buildings in Central Santiago. (Photo: Peter Smith).*

## 5.6 Concrete Floor Systems

Concrete floor systems in apartment and commercial buildings appeared to perform their diaphragm function well. However, in New Zealand we rely much more on the relatively thin (65–75 mm) concrete topping over precast elements to provide the diaphragm action. In Chile, the slab is cast in-situ and is more likely to be 150 mm thick.

Precast, hollow-core floor systems, where observed, performed well in high-rise commercial buildings. However, we did not observe its widespread use in apartment buildings. It was reported to us that Chilean practice is to reinforce alternate cores, propping the hollow-core units and then placing the support beam and topping in a single pour.



(a) Post earthquake (Photo: G. Segovia).

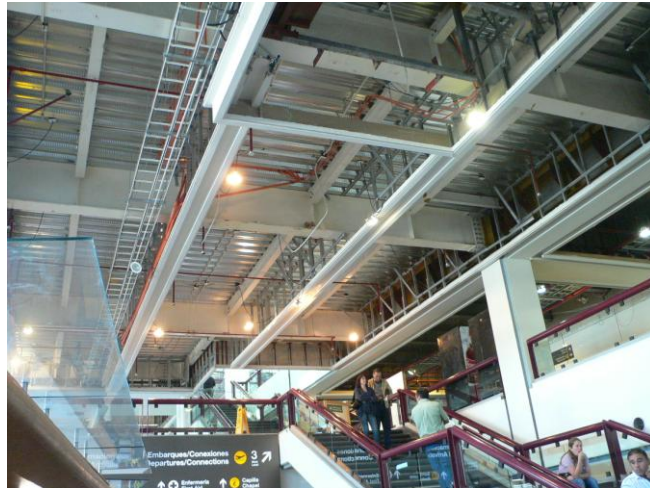
## 5.7 Ceilings and Ceiling Equipment

The team quickly became aware of the damage that had occurred to non-structural components on arrival at Santiago international airport. Even though it was two months after the event, suspended ceiling panels were missing in many places in the airport building (Figure 5.7) and there was obvious damage to mechanical and electrical equipment contained in the ceiling cavity (Figure 5.7d).

The direction of predominant motion and its relationship to the plant item can be critical to the behaviour of non-structural elements. For example, a lift motor in a badly damaged building that the team visited was still well mounted to its plinth (Figure 5.7e), whereas an identical unit in another building had suffered significantly (Figure 5.7f).



(b) Post earthquake (Photo: G. Segovia).



(c) On team arrival in May. (Photo: Graeme Beattie).

Figure 5.7a, b & c: Loss of ceiling tiles and damage to ceiling mounted equipment at Santiago International Airport.



Figure 5.7d: Santiago International Airport - air handling fan missing and damaged ducting. (Photo: Graeme Beattie).



(e) Motor still well restrained.



(f) Motor mounting has failed.

Figure 5.7e & f: Responses of lift motors to the earthquake. (Photo: Carl Lüders, SIRVE S.A.).

### 5.8 Seismic separation

In one Concepción apartment building where masonry infill panels had been used, the seismic separation detail formed by

using extruded polystyrene resulted in very significant structural and non-structural change (Figure 5.8a).

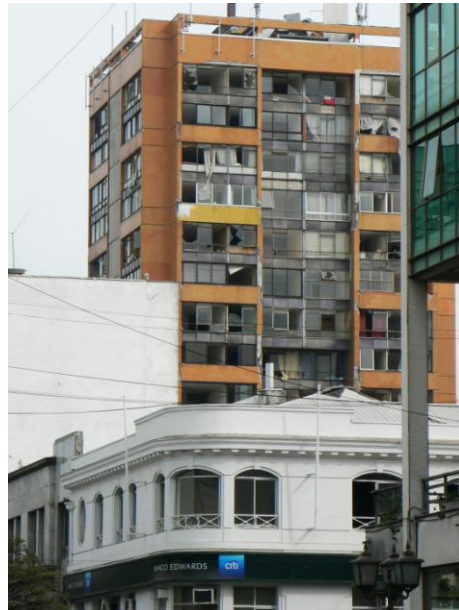


*Figure 5.8a: Seismic separation. (Photo: Peter Smith).*

### 5.9 Glazing

Many older multi-storey buildings had broken exterior glazing (Figure 5.9a). In these buildings the glazing is not an exterior curtain wall but discrete windows within the exterior frame of the building. Furthermore, the glass is cemented in place within the frame rather than being supported on spacer blocks in neoprene gaskets, so there is no tolerance for movement. When the floors of the building displace laterally with respect to each other during an earthquake, the glass cannot accommodate the displacement and fractures.

There are likely to be many older (1950s and 1960s) buildings in New Zealand of similar design that are likely to fare poorly in a major earthquake. These buildings may not yet have been identified as being likely to lose glass in a severe earthquake. The team's observations in both Concepción and Santiago were that curtain wall glazing systems on more modern buildings behaved very well (Figure 5.9b). This was corroborated by other foreign teams and by local engineers with whom we spoke.



*Figure 5.9a: Examples of buildings in Concepción with broken exterior glazing. (Photos: Graeme Beattie).*



*Figure 5.9b: Examples of curtain wall glazing that survived the earthquake with no damage in Santiago. (Photos: Graeme Beattie).*

### 5.10 Heavy Precast Exterior Cladding Panels

The connections between exterior wall panels of heavy precast concrete and the building structural frame are critical to a satisfactory performance in an earthquake. There were examples of buildings in Santiago where the precast panel

connections had failed and the panels had detached fully from the building frame (Figure 5.10). Such examples highlighted the need to ensure that the connection details have both strength to carry the loads and flexibility to accommodate the building displacements.



*Figure 5.10: (a) Precast panels with flimsy connections toppled at this convention hall near Santiago; (b) the same building before the earthquake. (Photo: G. Beattie and Juanelo242, Google Earth, respectively).*

### 5.11 Commercial and Industrial Racking Systems

The team were particularly interested in the behaviour of high-level storage racking systems because these are commonly used in some of our New Zealand supermarkets and also in our bulk retail outlets and home-handyman stores.

Several of the team talked with staff at a home-handyman store near our hotel in Concepción. The store was almost completely operational at the time of our visit, except for the lack of a heating, ventilating and air-conditioning system. We were advised that the racking system generally performed very well. One rack did rip the baseplate hold-down bolts from the concrete floor and overturn. This rack had heavy items such as toilet pans stored on the shelves and it was thought that the lateral inertial mass of these contributed to the failure of the shelving hold-down. The store is now instituting a policy of keeping heavier items stored at low levels on the rack system. Along the aisles, some loss of paint had occurred at the joints between the shelf beams and the columns, indicating that some yielding of the joint had occurred. This would have served to dissipate some of the earthquake energy. None of these joints appeared sufficiently damaged to require replacement.

We are aware of another example of a racking system carrying stacks of flat sheet material (José Restrepo pers. comm.) that had distorted in a lateral direction. The rack was attached to another rack that ran at right angles to the first, and which appeared to have pulled the hold-down bolts from the concrete. However, the details of the rack were obscured in the supplied photograph (not reproduced here) and it is difficult to tell the exact failure mechanism.

A great deal of the stock apparently fell from the shelves in the store. It was fortunate that the earthquake occurred in the



*Figure 5.12a: Fractured steel bracing cleat. (Photo: Carlos Aguirre).*

early hours of the morning, when the store was not occupied. While the loss of stock from low shelves may not be particularly dangerous to the public, it is important that items stored above the public (i.e., above 2 m) are adequately restrained from falling. Hinged doors and chains had been used on some of the top shelves to secure contents.

In New Zealand, suggestions such as the storage of heavy items on lower shelves are contained in the Design Guide on the “Seismic Design of High Level Storage Racking Systems with Public Access”, available for download free of charge from the Department of Building and Housing (DBH) or BRANZ Ltd websites. Positive restraint systems are imperative on high shelves of racking systems and recommendations for New Zealand store owners are made in the Design Guide.

### 5.12 Industrial Structures

Very little access was gained to industrial structures damaged in the earthquake. However discussions with people who had gained access soon after the event indicated that there was substantial damage that affected industrial production significantly.

Bracing gusset plates in concentrically braced frames (Figures 5.12a and b) appeared to have suffered brittle fractures in some instances perhaps due to out-of plane flexural/compressive sway. A number of grain silos fabricated from corrugated steel banding and steel posts collapsed in the Concepción area (Figure 5.12c).

The connection of roof bracing in some precast concrete industrial buildings failed and caused local damage.



*Figure 5.12b: Fractured steel gusset plate connected to a chevron-braced frame. (Photo: Carlos Aguirre, UTFSM).*



*Figure 5.12c: Collapsed grain Silos in Concepción. (Courtesy of A. García).*

## 6. COMPARISON OF CHILEAN AND NEW ZEALAND CONSTRUCTION CODES AND PRACTICES

### 6.1 Building Controls Regime

In line with global trends and local experience, seismic standards began to emerge in Chile during the 1930s with each earthquake spurring subsequent refinements. In New Zealand we have the Building Act, the Regulations and the Compliance Documents, whereas in Chile there is construction law, the ordinances (regulations) and the codes of practice.

The New Zealand Building Act is legislation dedicated to building and construction and is enacted by parliament, whereas Chilean construction law is based on a European code and legal precedents. Chile has national and local ordinances: the national ordinances are administered by the Ministry of Housing and Urban Development, and the local ordinances, which involve local building policy and bylaws, are administered by the municipalities. (Chile is divided into 15 regions, each headed by an *intendente* appointed by the President. The regions are divided into provinces, and these are in turn are divided into communes which are governed by municipalities elected by the local community).

In Chile the codes of practice are the next level down and the ordinances make some of these codes mandatory. The equivalent levels in New Zealand are the acceptable solutions and verification methods of the compliance documents. While the performance requirements in the compliance documents are mandatory, the verification methods and acceptable

solutions, which are essentially the Chilean code equivalents, are not mandatory. However, in New Zealand most designs are based on acceptable solutions or verification methods.

Secondary elements are defined in the Chilean seismic code as permanent elements that are not part of the resistant or primary structure but are affected by the primary structure movement. The examples of these elements given are: dividing partitions, non-structural façade elements, large windows, false or suspended ceilings, parapets, cornices, shelves, decorative elements, lamps, mechanical and electrical equipment etc.

The development of Chilean codes is similar to that in New Zealand. They are developed by the Standardization National Institute (INN), which appears to be an organisation similar to Standards New Zealand. Code development follows a similar process to that in New Zealand, with a committee of experts called together to develop or review the code, and there is also a public consultation phase. The final code proposal is approved by the INN council and it is then up to the Ministry of Housing and Urban Development or the Ministry of Works, as appropriate, to ratify the code, whereupon it becomes a Chilean Standard (NCh).

### 6.2 Compliance

The Chilean structural engineering codes and their New Zealand equivalents are listed in Table 1.

**Table 1: Comparison of current Chilean structural Codes and New Zealand Standards**

	Code Number	Code Type	Current version	Equivalent New Zealand Standard	Current Version
<b>Actions</b>	NCh 431	Snow loading	1977	AS/NZS 1170.3	2003
	NCh432	Wind Loading	1971	AS/NZS 1170.2	2002
	NCh 1537	Dead and Live Load	1986	AS/NZS 1170.1	2002
<b>Materials</b>	NCh 427	Steel design	1977	NZS 3404:1997	2007
	NCh 430	Reinforced concrete design (based on ACI 318)	2008	NZS 3101:2006	2006
	NCh2123	Reinforced masonry	2003	NZS 4230:	2004
<b>Earthquake</b>	NCh433	Earthquake resisting design of buildings	1996	NZS 1170.5	2004
	NCh2369	Earthquake resisting design of industrial structures and facilities	2003	No Standard but some coverage with NZS 4219 and NZS 3106 and recommendations for tank design	2008 2008 2010
	NCh2745	Earthquake resisting design of base isolated buildings	2003	No Standard	

As can be seen, some of the Chilean codes are quite old. This does not necessarily mean they are incorrect, but in New Zealand reviews are carried out more frequently, so Standards are more up to date. For example, it appears that the Chilean wind loading code hasn't been revised for nearly 40 years. Note also that New Zealand does not have separate Standards for dedicated industrial structures nor a base isolation Standard as is the case in Chile, where hi-tech buildings performed very well.

The Chilean seismic code NCh 433.Of. 96 allows an equivalent lateral force procedure with amplified torsion or a modal analysis based on the response spectrum, so it is similar to common practice in New Zealand. It also contains a mandatory section on the design of secondary structural elements.

In general there will be a reduced torsion demand on medium- and high-rise New Zealand buildings—and hence less damage resulting from this aspect—than with Chilean buildings. This is because the Chilean seismic code has no restrictions on irregularities, whereas the New Zealand seismic Standard does.

Much of the damage to medium- and high-rise buildings in Chile was due to inadequate ductile detailing, particularly when a large reduction in earthquake base shear is permitted by the Chilean seismic code. Where New Zealand buildings have been designed for reduced earthquake base shear, the Standard requires appropriate detailing of primary members to ensure a ductile response. Assuming these New Zealand buildings have been well designed and constructed, their performance should be significantly better.

The overall good result in Chile would appear to have been due to the fact that most buildings are of shear wall construction, as opposed to concrete frame construction where there is less redundancy. In New Zealand there are more

concrete frame buildings, so there is less redundancy to offset critical structural weaknesses.

One of the main reasons for the poor performance of some Chilean buildings is undoubtedly inadequate confinement (transverse) reinforcement provisions applying to walls and columns. The Chilean concrete code is based on the ACI concrete code, but the provisions for spacing of transverse reinforcement around vertical bars at the ends of shear walls were relaxed after the apparently good performance of buildings observed during an earlier magnitude 8 earthquake in central Chile on 3 March 1985.

### 6.3 Approval to Build

The process to obtain approval to build in Chile is similar to that in New Zealand. Project drawings (architectural and structural) and specifications are submitted to the local municipality for approval. There are no non-specific design codes, so all applications are specific designs by various people in the building industry.

The municipal check consists of a documentation check in which the building controls officer will check that the central government and local municipality ordinances and building policy have been complied with. That is an urbanisation rule or district plan rule check would be carried out together with a check that each project (specific design) has been signed off by an appropriate building professional. One of the criticisms in Chile is that the quality of the design is not assessed and often critical aspects are overlooked. In New Zealand this situation is slightly different, in that many applications for consent are non-specific designs, particularly with residential construction. Thus, in addition to the RMA and local policy checks, the building controls officer needs to check that the design conforms to the Standard or the building code acceptable solution.

In Chile all public utility buildings (schools, hospitals, police fire, communication buildings, etc.) and office and residential buildings over five stories in height are required to have a peer review. Peer reviewers must meet specific criteria for pre-requisite experience for particular building categories—details of qualification requirements are given in Table 2.

This requirement was introduced in the general construction ordinance (law of country) in 2003. In New Zealand there is no mandatory requirement, but most multi-storey buildings get peer reviewed one way or another, so the effect is the same. For example in Wellington city a regulatory review is carried out in which the council use the services of a local consulting engineering practice to peer review the design. In Auckland city it is understood that compliance is based on a formal peer review by another consulting engineering practice, i.e. producer statements or, more in particular, an IPENZ PS1 and PS2 is used by the council to establish compliance. In addition, consultants who design these buildings will often carry out an in-house peer review as well.

Once Chile municipalities are satisfied that compliance with all the ordinances has been established, they will issue a construction permit that is similar to the building and resource consents issued in New Zealand once the Building Consent Authority is satisfied of building code and resource management compliance.

#### 6.4 Construction

In Chile, inspections for a peer-reviewed building are mandatory, whereas inspections for other buildings are at the discretion of the owner/designer.

**Table 2: Chile Government requirements for the qualification of peer reviewers of buildings (interpretation of Chilean table).**

Category	Experience			Peer review limitations
	Years (min)	m <sup>2</sup> floor area	No. of buildings	
1	12	150,000 in the last 10 years	5 buildings but 10,000m <sup>2</sup> for each one in the last 8 years	No restrictions
2	8	100,000 in the last 10 years	3 buildings but 8,000m <sup>2</sup> for each one in the last 5 years	Buildings up to 15,000m <sup>2</sup>
3	5	50,000 in the last 5 years	3 buildings but 5,000m <sup>2</sup> for each one in the last 3 years	Buildings up to 10,000m <sup>2</sup>
Geomechanics	12	Geomechanics Engineer specialist in soil mechanics		Any building

## 7. COMMENTS AND ISSUES FOR NEW ZEALAND BASED ON CHILEAN EXPERIENCE

### 7.1 Building Controls and Governance

The Chilean building controls regime is similar to that in New Zealand. In Chile the code requirements for secondary structural elements and the seismic restraint of engineering systems are not always being met and it would appear there is limited restraint of non-structural elements. In New Zealand, as in Chile, we need to raise awareness about the importance

A log of inspections is provided to the local municipality at the completion of the project. One of the major criticisms in Chile is that the level of inspection or supervision of smaller buildings, including residential construction, which is not covered by the mandatory peer review process, is poor. In New Zealand consulting engineers and Building Consent Authorities tend to use the IPENZ construction monitoring protocols (based on job size, importance, complexity, experience of contractor, etc.), or other similar bases for specifically designed buildings such as multi-storey buildings. They will often request an IPENZ PS3 or a PS4 producer statement as evidence that sufficient construction monitoring has been carried out. Inspections for smaller buildings, such as non-specific designed housing, is done at critical stages by the Building Consent Authorities.

In Chile only alterations involving architectural changes need to be approved: other alterations are noted, including structural alterations, and recorded on as-built plans and submitted to the municipality at the end of the job. This increases the risk of unacceptable (e.g., structural) changes being carried out. Fortunately, in New Zealand any significant alterations to the design during construction require details to be resubmitted to the Building Consent Authority for approval.

In Chile, a municipal reception is issued once they are satisfied the building is complete and built in accordance with the requirements. This is the Chilean equivalent of the New Zealand Code Compliance Certificate.

of secondary and non-structural element design for earthquakes. Although there are code requirements, it is suspected that there are new buildings in New Zealand in which the structural design of these aspects has not been considered. The reasons for this are probably the same as in Chile—the owner has not requested this design work to be done or the design work has been done but the installation has not followed the design. In addition, the Building Consent Authority and/or peer reviewer may not have picked up the omission.

While the Chilean seismic code has specific requirements for establishing criteria and procedures for evaluating earthquake damage, for earthquake strengthening and for the repair of earthquake damage to buildings, there is no level or levels to

which buildings must be strengthened to. As in Chile, New Zealand needs to develop requirements for the level of repair and retrofit. After the earthquakes in Canterbury and Gisborne, the extent of repair to damaged buildings is being dictated by insurance policies and the earthquake prone building policies of the local authorities. In Christchurch the minimum target strength level is currently set at 67% but this may be varied after assessment of relevant factors. In Gisborne the level is also 67% and there has been some confusion as to what extent insurance cover repairs to this level.

The non-mandatory New Zealand regulatory review process appears to be working well and is similar to the mandatory peer review process in Chile. The difference is that the New Zealand review applies to all buildings. In Chile, however, buildings not subject to peer review, such as low-rise buildings and housing, appear to be more at risk of not meeting a satisfactory level of earthquake resistance because regulatory audits for these buildings appear to be less onerous than in New Zealand.

In Chile there appears to have been a poor level of monitoring of construction of non-public buildings. No records of building damage appear to be kept at Municipalities, making it difficult for potential buyers to know whether a building has been damaged and, if repaired, the details of the repair. In New Zealand this information is lodged on the Land Information Memorandum (LIM).

There is no policy for systematic consideration of the risk posed by seismically vulnerable buildings in Chile, as introduced to New Zealand in recent years. The 2004 Building Act required all territorial authorities to put in place policies on earthquake-prone buildings by mid-2006 and to review those policies within five years. The intent of the legislation is to reduce the level of earthquake risk to the public over time; it targets the most vulnerable buildings and aims to improve their performance. The district and city councils are permitted to tailor policies to suit local perceived hazard levels and social and economic conditions.

## 7.2 Codes and Compliance

The Chilean codes share with New Zealand Standards the life-safety objective which, in the case of the February 2010, Chile and 2010-2011 Canterbury earthquakes was largely achieved, even though the shaking probably exceeded the design demand levels at many sites. There were a low number of building failures in both Chile and New Zealand. There are, however, recognised deficiencies with the Chilean seismic and material codes, principally related to the detailing requirements for reinforced concrete.

Good earthquake performance in the past (particularly during the 1985 Valparaiso earthquake) had allowed some requirements (e.g., confinement in shear walls) to be relaxed in later years and this contributed to poor performance in a number of cases inspected by the team. As a lesson for New Zealand, reinforced by the experience of Canterbury within the current year, this highlights the importance of determining performance with reference to actual ground motion intensity (the value of seismic monitoring), and the impact of dominant period relative to building period and subsoil conditions.

## 7.3 Legislation for Restraint of Non-structural Components

New Zealand has had provisions in its loading standard for non-structural components for more than 30 years. In the early versions of NZS 4203 the section was titled "Parts and Portions". Since the introduction of NZS 1170.5 the section of the seismic loadings standard has been titled "Requirements for Parts and Components".

The Chilean Earthquake Loadings Standard NCh 433.Of.96 has also had provisions covering the design of "Secondary Elements" since at least 1996. Three performance levels are identified (Excellent, Good and Minimum) and a performance factor  $K_d$  of 1.35, 1.0 and 0.75 is used respectively in the calculation of the design forces. The required performance level and the occupancy category of the building determine the level of the  $K_d$  factor.

The secondary elements and their anchorages to the resisting structure are to be designed for a horizontal seismic force acting in any direction given by:

$$F = Q_p C_p K_d,$$

where  $Q_p$  is the shear developed at the base of the secondary element, in conformance with an analysis of the building that has included the modelling of the secondary element. The  $C_p$  factor is tabulated and ranges from 0.7 to 2.0, where 0.7 relates to low risk to life elements and 2.0 to high risk to life elements.  $K_d$  is the Performance Factor and is tabulated depending on element type and also building class. Buildings are classified as either A, B, C or D.

Class A is the highest Chilean classification and covers government, municipal, or public-use buildings (e.g., police stations, telephone exchanges) and those buildings whose use is of special importance in the event of a catastrophe (e.g., hospitals, fire stations)—much like importance level 4 in AS/NZS 1170.0. Class B structures are those that house large numbers of people (e.g., assembly halls) or hold high value contents (e.g., libraries), again much the same as importance level 3 in New Zealand. Class C structures are all other structures not included in Class A or Class B (equivalent to New Zealand importance level 2), except those that are not intended for living and are temporary – Class D (New Zealand importance level 1).

Therefore, the horizontal force acting on the secondary element may be as high as  $1.35 \times 2.0 (=2.7)$  times the shear at the base of the secondary element. This shear may well be amplified above the shear at the base of the building, and this amplification could be as high as 2. Compare this with the New Zealand Standard, which requires that the Part be subjected to a force of up to a maximum of 3.6 times the weight of the part.

The key point is that both countries have standards for the design of seismic restraints for building services and non-structural elements. New Zealand has the dedicated Standard NZS 4219:2009 which was cited in the New Zealand Building Code on 1 August 2011. This standard is an application document for NZS 1170.5, which is cited by the Building Code. Therefore, there is a legal requirement to carry out a design for restraints of non-structural elements, and until it can be proven that this has been done the Code Compliance Certificate should not be issued by the Local Territorial Authority. The legislation in Chile is very similar.

However, it is the authors' belief that in both countries little consideration is given to this requirement, and the follow-up needed to check if it has been done; as a result it often goes unchecked. A key question for advocates of more stringent oversight in both countries in the past has been how to convince the industry that greater consideration must be given

to the non-structural components. The people likely to be most affected by the failure of non-structural systems are business owners, who may be occupying a “safe” building but cannot conduct their business because the services are seriously damaged.

In the wake of severe economic losses in Chile and Canterbury, interest in performance levels for amenity and cost-effective strategies for reducing damage is broader than ever before.

#### 7.4 Design Guidance

In Chile, apart from some general guidance in the seismic code there appears to be very little guidance on earthquake repair and retrofit solutions, e.g., shear wall strengthening. In New Zealand there is significant literature, including case studies that deal with this topic, but knowledge of the options remains largely confined to the structural engineering profession. The result of this being that applications are not as widely considered and beneficial as they might be in a country with high seismic hazard.

## 8. TRANSPORT LINKS AND ESSENTIAL SERVICES



*Figure 8.1: Damaged road near Concepción. (Courtesy of A. García).*

The response to non-concession road damage was handled at a local level by MOP staff and contractors. The public were notified of route closures and alternate routes using all available media, including the MOP advisory web site and Twitter. Construction materials were being restocked prior to winter, so their supply was not a problem. Fuel was accessed locally and some problems of supply for construction machinery were experienced, but only where there were general shortages. The first response was to put some form of

### 8.1 Roads, and Road and Rail Bridges

The Ministry of Public Works (Ministerio de Obras Públicas - MOP) is the cabinet-level administrative office in charge of planning, directing, controlling and building the public infrastructure, as well as the conservation and management of them within Chile. MOP is also responsible for the management, distribution, use and conservation of all the water resources within the country. Since 1993 the MOP has overseen a significant expansion of public-private-based infrastructure developments (PPP's), which include highways, airports, public buildings, and Santiago's public transport system, with initiatives totalling approximately US\$9 billion.

#### 8.1.1 Roads

Lateral spread and settlements were the major causes of damage to 100 km of concession roads and 3,000 km of MOP-controlled roads (Figure 8.1). Horizontal movements and vertical settlements of up to 8 metres displacement occurred at some locations. Only two major slips were reported following the earthquake and this low number is thought to be a result of the long period of dry weather Chile had experienced prior to the earthquake, which meant water tables were relatively low.

temporary access in place so that initially single lane routes and temporary approaches to bridges were usable.

#### 8.1.2 Road Bridges

Before the mid-1980s, the bridge design code in Chile was based on the provisions of AASHTO Standard Specifications of that time, with a seismic coefficient of 0.12. This coefficient was increased to 0.15 following the  $M_w$ 8 1985 Valparaíso (central Chile) earthquake, and a modified version of Division I\_A of AASHTO Standard Specification was

adopted in 1998. The design coefficient was not, however, changed until 2001, when three seismic zones were introduced, with peak ground accelerations of 0.2, 0.3, and 0.4. Columns were required to be designed to the requirements for the higher Performance Categories C and D of Division I-A (EERI, 2010). In 2002 Chile adopted its own bridge design manual for public and concession road and pedestrian bridges (Chile MOP).

Damage to bridges in the February 2010 earthquake was widespread but in isolated pockets. Of the 2,169 bridges on concession routes, 101 were damaged, with 63 closed. Of these, 20 needed to be demolished, while another 20 required extensive repairs. The only bridge that totally collapsed was an historic stone arch bridge. 300 MOP-controlled bridges were damaged.

The most common damage to bridges was due to lateral spreading and settlements of foundations, with decks displacing and falling off pier supports, piers settling and displacing, and a few shear failures of pier columns. Very few highway bridges were affected by the tsunami, but the piers of one bridge were reportedly scoured by the out-flowing tsunami.

Road bridges founded on marine sediments suffered from liquefaction-induced damage and the team was made aware of several instances where bridge beams separated from the abutments or piers during the earthquake (Figure 8.2). Bridges constructed to pre-1990s Chilean standards generally performed much better than those constructed since by foreign concessionaires. The earthquake exposed a number of ‘as built’ inadequacies in the latter — these included the lack of deck diaphragms over piers, inadequate beam seating widths and insufficient deck restraints to resist seismic uplift at piers. These features resulted in large deck displacements, with a number of decks collapsing from their supports (Figure 8.3).

It appeared to the NZSEE team that there were no links between the beams and the piers or abutments that would have resisted the tendency for the beams to slide off the piers — a style of failure reportedly common at a number of bridges where the decks were seated obliquely with respect to the piers. It was reported that for footbridges, construction was not

detailed for earthquake loadings to the same extent as for road bridges. Consequently a higher proportion of footbridges were damaged.

Highways which had been upgraded by concessions to a dual-lane carriageway in each direction featured duplicate two-lane bridges at major crossings. Fortunately, at most locations at least one bridge remained operable following the earthquake and after repairs to approaches the highway was once again passable.

All bridges across the Bio Bio River at Concepción were closed after the earthquake (Figure 8.4). The oldest bridge (*Puente Viejo*), which had already been identified as deficient in seismic resistance and closed before the earthquake had several of its spans collapse (Figure 8.5). Ramps at one end of *Puente Llacolén* were unseated due to a combination of either lateral spreading or out-of-phase movements. A bailey bridge was erected over the one fallen span and the bridge re-opened (Figure 8.2). *Puente Juan Pablo II* is an older bridge and experienced major settlement of isolated piers and lateral spreading of the bank at the eastern end, leading to the shear failure of a pier column. It remained closed to vehicular traffic at the time of our visit.

Chile’s manual for the design of bridges is currently being reviewed, with consideration to micro-zoning of earthquake response for bridge sites and possible local magnification effects. New Zealand has a bridge design manual and an active seismic screening and retrofit programme for State Highway bridges which reduces the potential for damage similar to that sustained by bridges in Chile.

### 8.1.3 Rail and Rail Bridges

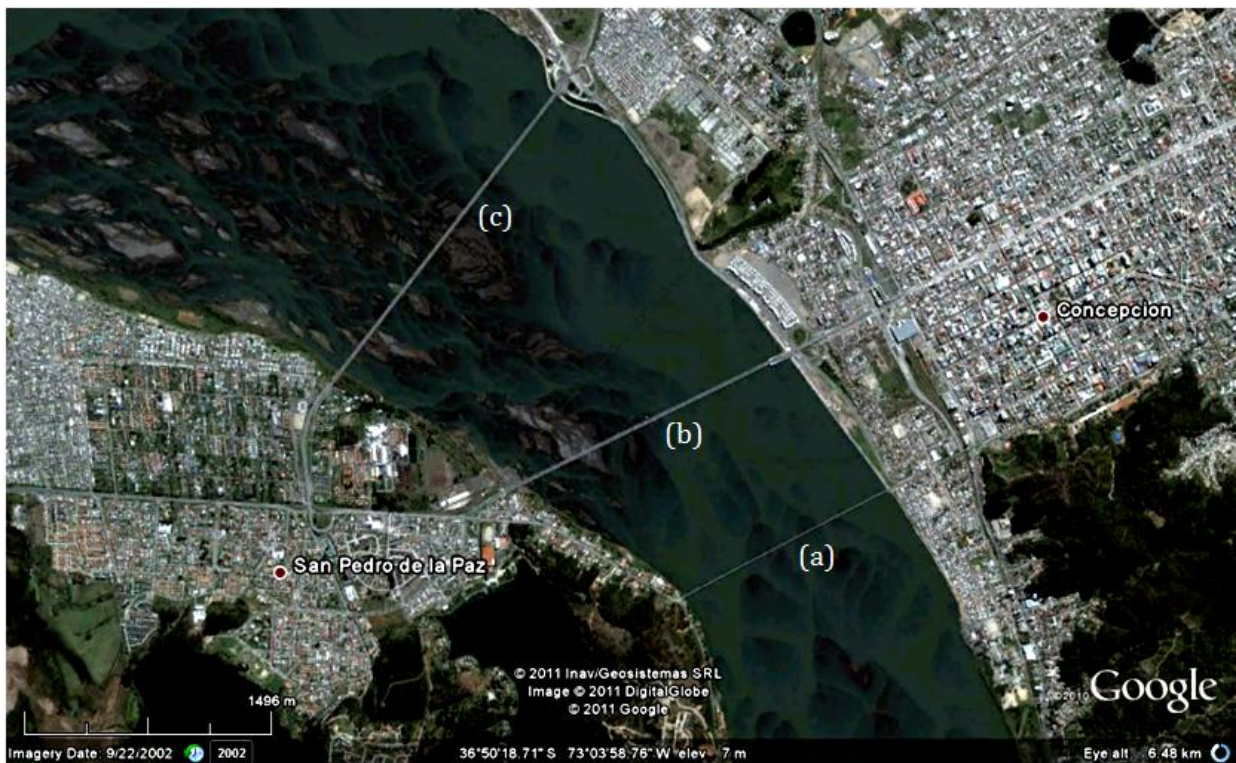
In general railroad bridges performed better than highway bridges, perhaps due to their structural steel construction or design for higher live loads. The eastern approach pier to the Bio Bio River rail bridge at Concepción moved towards the river, but did not drop the steel truss superstructure, which was shored up with a stack of railway ties after the earthquake (EERI, 2010).



Figure 8.2: Bridge deck collapse and a bailey span repair in Concepción. (Photo: Graeme Lawrence).



**Figure 8.3:** Collapse of a bridge deck on the Santiago ring-road “Vespucio Norte”, due to lateral rotation of the obliquely-seated deck and absence of diaphragms. (Photo: Ministerio de Obras Públicas).



**Figure 8.4:** Damage to the bridges crossings Bio Bio River in Concepción imposed severe constraints on traffic flow, retarding the initial recovery effort. (a) Puente Viejo road bridge, (b) Llacolén road bridge and (c) Juan Pablo II road bridge. (Image: Google Earth).



*Figure 8.5: Collapsed bridge across Bio-Bio River. (Courtesy of A. García).*



*Figure 8.6: Replaced linkspan from access roadway to terminal. (Photo: Graeme Beattie).*

## **8.2 Airports**

### **8.2.1 Concepción Airport**

The airport at Concepción experienced only minor damage to the terminal building due to water damage caused by a broken sprinkler system. The airport remained operational for armed forces' emergency flights, which peaked at 340 take-offs or landings per day. National carrier LAN Chile ceased all flights to and from Concepción for the first five days, which eased access for military relief flights. (TCLEE, 2010)

### **8.2.2 Santiago Airport**

As described in Section 5.8 the airport terminal building in Santiago suffered major collapse of suspended ceilings (see

Figure 5.8), but no obvious damage to its structural steel frame. However, pedestrian bridge spans linking the suspended access road structures and the main terminal entries dropped off their supports in a number of places due to lateral differential movement between the terminal building and the suspended road structure (Figure 8.6). The potential for such damage at Wellington during a major earthquake should be evaluated.

The benefit of having practised emergency response exercises was demonstrated at Santiago Airport. Santiago Airport is managed by the Civil Aviation Authority (CAA), with the terminal building privately administered under a concession. After the earthquake an emergency plan that had been

practised for accidents, pandemic and earthquake was activated in which the CAA took control of the whole airport.

The only damage to the CAA-controlled area was structural damage to the control tower cabin. Control operations were immediately transferred to the two-storey former control building, which was kept in reserve. An inspection of standing areas (with some minor spalling of concrete slabs), taxi ways and runways took 20 minutes and they were cleared to resume further activity. One emergency air ambulance flight did take off in the early morning of the earthquake. The Chilean Air Force base on the airport was used as a base for many emergency operations and aid flights that started from there on the first day.

In the aircraft fuel compound, a water tank supplying water for foam fire-fighting collapsed and two fuel tanks leaked through non-flexible valves. The leakage was intercepted by the surrounding bunds and the fuel retained in the leaking tanks was pumped into the two remaining good tanks. Airlines were initially informed that no fuel would be available at the airport, but after emergency repairs the lines were checked and fuel was available for aircraft three days after the earthquake.

One lesson learned was the benefit of having back-up systems for handling aircraft and passengers. Extensive non-structural damage to the terminal building meant that passenger processing, customs and immigration activities were totally disrupted and no passenger flights could be processed. The terminal building was closed as a safety and security measure—the airport fire service cleared all buildings of people and police patrols closed off all access.

The airport then set about getting passenger flights reoperating, which was hampered by the lack of any back-up to the aircraft marshalling, passenger processing, and immigration and customs systems. Initially staff had to revert to manual systems, which slowed the restoration of flight services. Within a day, passenger processing was established in two large tents erected on paved areas. The airport had



**Figure 8.7a:** *Pile heads broken away from wharf deck steelwork at Puerto Coronel. (Photo: Clark Hyland).*

previously bought a supply of VHF radio cell phones for emergency communications and these worked well, and as all telephones were either overloaded or out of service they proved invaluable. Departures were back to normal numbers six days after the earthquake.

A report on the response by CAA noted that in the first three weeks of the emergency no special staffing schedule was necessary. Everyone worked until they could do no more each day. The commitment of the staff, who worked every day till exhausted, was duly recognised.

### 8.3 Ports and Wharf Structures

#### 8.3.1 Coronel

The Coronel Port, 40 km south of Concepción, was affected principally by earthquake shaking damage, with permanent ground deformation extending in an offshore direction. The total width of cracks due to lateral spread measured on site was 1.5 metres. No structural damage was noted on the south pier, which is a recently opened, base-isolated structure with rail-mounted gantry cranes, although its conventional access pier suffered some slumping damage at the shoreline. The north pier, however, and particularly the abutment link span suffered damage due to the lateral displacement by the sea floor of the circular steel section piles, which in places broke the welds fixing the piles to the soffits of the steel beams that support the deck.

There was evidence of some piles beneath the wharf shearing off. The slumping of the reclaimed soil at the shore had pushed the piles nearest the shore seaward (Figures 8.7). The wharf could not be used by service traffic and the ducts for services to the boats were broken. The wharf company was repairing the wharf by cutting holes in the concrete deck and driving new steel piles, which were then welded into the existing deck structure (Figure 8.8).



**Figure 8.7b:** *Pile head deformed due to abutment shunting caused by liquefaction. (Photo: Clark Hyland).*



**Figure 8.8:** Repairs to the north pier at Coronel Port consisted of driving new steel piles and welding them to the existing deck structure. (Photo: Hugh Cowan).

### 8.3.2 Talcahuano (Concepción Area)

At Talcahuano, substantial damage was caused by the tsunami. Buildings, warehouses and commercial fishing facilities along the waterfront were flooded by water and battered by debris (EERI, 2010). The piers and cranes at the Naval Base and ASMAR dockyard nearby were damaged by large naval ships and barges uplifted by the tsunami (EERI, 2010).

## 8.4 Water Supply and Sanitation

Essbio S.A. is the water supply and wastewater concessionaire for the Bio Bio region, with two water supply treatment plants, one of which is for Concepción City and environs, and a number of wastewater plants around the region. At Concepción it has between 50,000 and 60,000 customers, including residents and industry.

### 8.4.1 Water

Essbio takes water from the Bio Bio River to a treatment plant capable of producing 250,000 cubic metres a day, but which normally operates at about two-thirds capacity. Treated water is pumped by two mains to a single reservoir and thence to a distribution network.

Even though Essbio had not specifically prepared itself for a damaging earthquake, it responded well to the situation. The plant had standby generators capable of operating the plant at one-third capacity, and was being expanded to full capacity at the time of our visit in May 2010.

The earthquake caused damage to the building housing the inlet and outlet pumps, including significant cracking to the reinforced concrete frame/brick infill structure and about 200 mm of lateral displacement of the inlet section of the building from the outlet section. Fortunately no underground water mains traversed the line of displacement under the building. The building was so damaged that, as well as temporarily propping the building, each major item of plant was secured

by a surrounding structural steel frame to protect it from a possible collapse of building components due to aftershocks (Figure 8.9).

The control building suffered some damage, but the control equipment was not affected. A lesson learned was the importance of having backup control capability.

The mains feeding the reservoir were broken at eight locations due to lateral spreading, especially along the banks of the Bio Bio River. The reservoir was undamaged, but without automatic shut-off valves all the stored water drained out. Fire-fighting hydrants for Concepción, which are fed from the public system, were without water, as was the entire network. Fortunately there was no fire following the earthquake. It took four days to repair the lines to the reservoir.

Essbio has an emergency plan in which the local manager takes control. The local manager was supported by the company chairman, who flew in from Canada. He provided support with on-the-spot approvals and took on a public relations role. Of the 121 company workers, 41 had lost their homes.

Distribution of water was a priority. As many as possible, 1.5-cubic-metre plastic containers were purchased and placed around the town. They were filled by a fleet of hired mobile tankers, which also serviced hospitals and other critical facilities. Water became a critical supply and the company was forced to call for armed military guards around the water compound.

Communications to outside the region were not established until a day later. The purchase of radio-telephones was absolutely invaluable for the restoration. Local contact was made through the one operating local radio, which initially became the call centre for major utilities. Fuel was not delivered to the water compound until six days after the earthquake.



**Figure 8.9: Propping and steel frames built to protect pumps in ESSBIO water plant. (Photo: C. Oyarzo-Vera).**

Essbio engaged 15 public relations staff during the restoration phase. A decision was taken to always deliver positive news to reassure consumers that progress was being made. However, with the uncertainty of the location of all pipe ruptures, care was also taken not to create unrealistic expectations of when suburbs would be reconnected. The restoration process was often delayed by the discovery of new breaks once water was once again flowing through the lines. Seventy breaks to large-diameter steel pipes were repaired, along with local steel distribution mains, while the 2 to 3 km of asbestos cement pipes in the network were replaced with high-density polyethylene (HDPE) pipes (see restoration curves in Figure 9.2). Water connection laterals, from meters to households is the responsibility of house owners and the minimum cost of those repairs was estimated to be US\$0.5 million.

#### 8.4.2 Wastewater

The damage to the wastewater network included a collapse of the infill joints between the precast elements of the main chamber at the Concepción treatment plant, breakages of various sewer mains and the uplift of a number of buried chambers due to the effects of liquefaction of surrounding soil and the breakage of many sewer mains – much as witnessed in eastern Christchurch and Waimakariri District during the past 12 months.

It was estimated that the treatment plant would be out of action for a period of about a year, so emergency outfalls to the Bio Bio River were allowed to prevent the remaining system from backing up and overflowing. In some locations emergency overland pipes were placed where the underground mains were broken between chambers, which were later enlarged as required.

### 8.5 Energy Supply

#### 8.5.1 Gas

Gas is distributed by concessionaires in Chile. The Bio Bio region is supplied with natural gas via a pipeline from Argentina. While no interviews were held with the Concepción concessionaire, it was evident from street works that the network of brittle steel gas mains was severely disrupted in the Concepción downtown area. Three months after the earthquake, contractors were still working to replace

the entire network in high-density polyethylene pipe, and the gas company was still reconnecting one street at a time.

#### 8.5.2 High Voltage Grid

Even more so than New Zealand, the geography of Chile is long and narrow with an electrical system to match. The system is divided into four separate grids that are geographically isolated and as such operate independently of each other. These systems are not interconnected and cannot be readily interconnected. Figure 8.10 shows the location of each system with respect to the location of 27 February 2010, Maule earthquake. The central region *Sistema Interconectado Central (SIC)* supplies approximately 69% of Chile's power requirements to 90% of the population and was directly affected by the earthquake.

The SIC system primarily comprises thermal and hydro generation (approximately 6,300 MW capacity), with 500 kV and 220 kV "Trunk" transmission and 154 kV, 110 kV and 66 kV sub-transmission. Therefore the amount of generation and power transmission of this system is comparable in size and nature to that of New Zealand. Generally the transmission system in Chile performed well and power was readily reinstated. Damage was sporadic and generally affected only older items of plant from the 1960s and 1970s (Figure 8.11). While the seismic performance of the equipment in Chile is encouraging, the level of ground shaking (peak ground accelerations) experienced along the trunk/core grid was only about 50% of the ground shaking levels designed for in New Zealand.

The ability to transport replacement equipment and parts to key substations may be hampered by disruption to infrastructure, such as damaged roads and bridges. On this occasion it was not critical in Chile, as the majority of the core grid was about 80 km from the coast/disaster zone, but it could be more critical in the New Zealand setting where the core grid is in proximity to major fault lines. Emergency power supplies such as batteries and diesel generators to run crucial auxiliary equipment also have a limited duration, so depending on the extent of damage from a large earthquake and the length of time needed to restore the system, fuel and back-up power supplies may be insufficient.

Another lesson arising with the benefit of hindsight is the value of attention to detail during design and construction to

mitigate damage to critical plant. For example, a number of post insulators supporting a flexible bus failed at a Chilean substation, swinging down and striking other equipment. While the bus was readily repaired, the damaged equipment had to be by-passed until new plant could be purchased. There were a number of line pull and jumper connection failures, which could also be attributed to poor jumper geometry.

The ability to isolate each area of the Chilean grid into a self-sustaining area worked well, but was possible primarily because of the even distribution of power generation along the length of the country. This highlights the potential

vulnerability of New Zealand's power system, as little power is generated near the two main metropolitan areas of Auckland and Wellington.

No significant power assets were in the direct path of the tsunami in Chile, but the impact of a tsunami on a substation would be devastating and New Zealand's grid operator, Transpower, does own and operate substations in a number of coastal areas. It may be prudent to quantify the risks of the potential impact of tsunami on the New Zealand power transmission system as a whole, should a coastal substation be flooded.

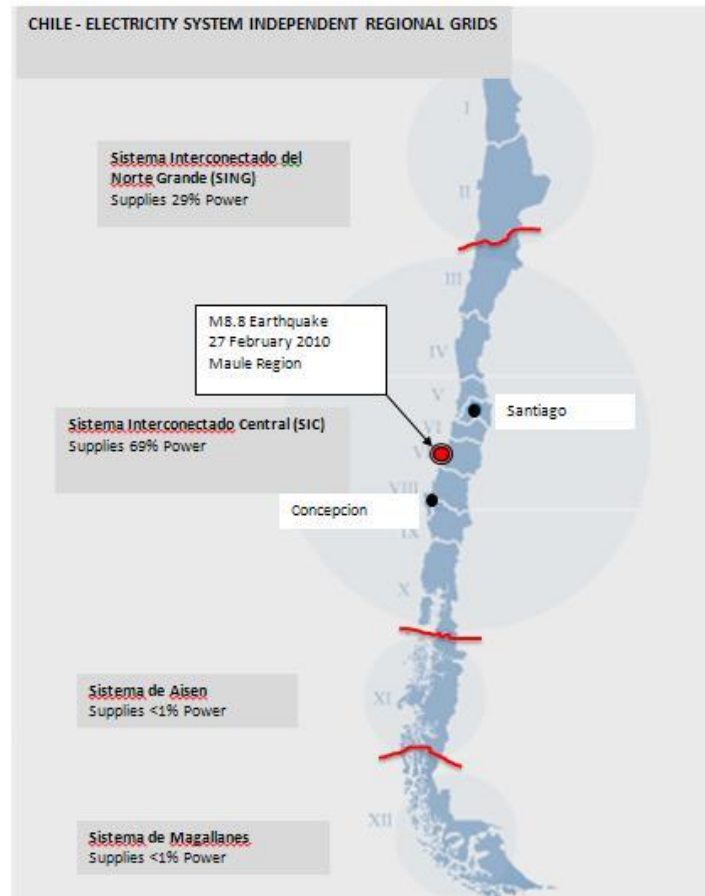


Figure 8.10: Chilean Electrical System Regions. (Source: Transelec).

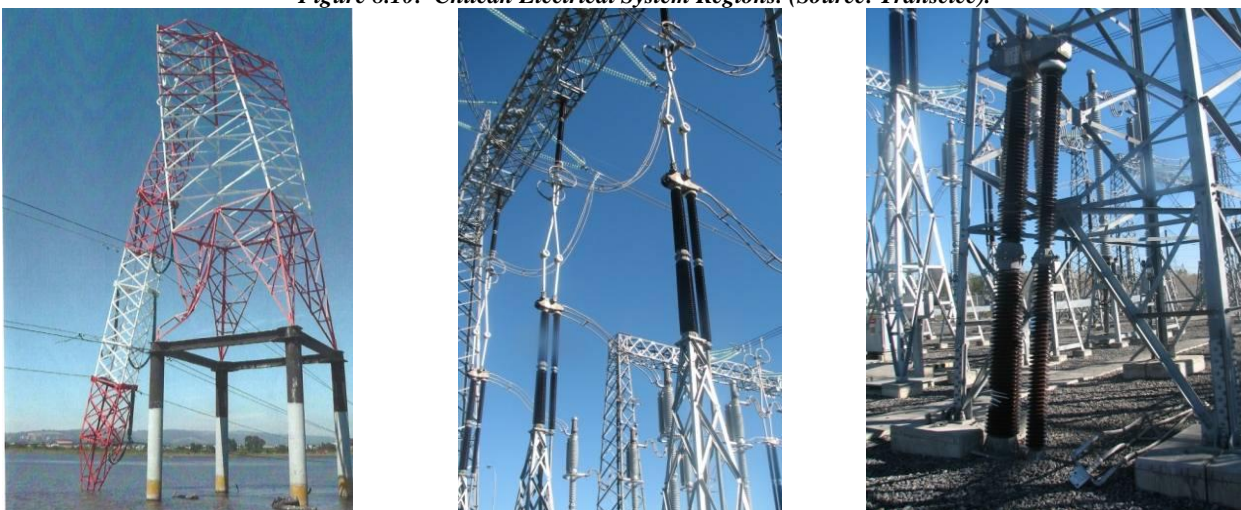


Figure 8.11: Concepción – San Vicente 154 kV pulled over transmission tower (left); Charrua Substation - In service (centre) and failed (right) disconnectors. (Photos: Transelec).

## 9. DISCUSSION

The unique attributes of the Chile earthquake – its size and duration of shaking – are related to its tectonic setting in a zone of plate under-thrusting (“subduction”), offering clues to the potential effects of a similar, although perhaps slightly smaller New Zealand event. Unlike Chile, which has experienced multiple historical subduction zone events, New Zealand has not experienced a large subduction earthquake in the North Island region in written memory (up to 200 years). All of New Zealand’s largest recorded earthquakes have been related to faulting in the crust of the overlying Australian plate, but recent advances in geodetic monitoring and analysis have indicated that the Pacific and Australian plates are “locked” beneath the southern North Island (Figure 9.1), over a region 90-180 km wide and extending to a depth of ~40 km (Reyners and Eberhart-Phillips, 2009; Wallace *et al.*, 2009).

The rupture area of the 2010 Chile earthquake was anticipated a few years earlier from the analysis of similar geodetic patterns (references) although the timing of a future subduction earthquake in New Zealand remains uncertain because so little is known of its prehistoric behaviour. We can say that the plate interface beneath the southern North Island appears to have the potential to generate earthquakes of magnitude 8.2-8.7. It is also important to note that the “locked patch” lies not beneath the ocean as in most comparable geographic settings elsewhere, but directly beneath the land and therefore closer to centres of population.

The cause for interest and concern is that high inter-seismic coupling has been identified in the Hikurangi subduction zone – that is to say, the Pacific and Australian plates are “locked” beneath the southern North Island (Figure 9.1), over a region 90–180 km wide and extending to a depth of c. 40 km (Reyners and Eberhart-Phillips, 2009; Wallace *et al.*, 2009). The rupture area of the 2010 Chile earthquake was anticipated a few years earlier (Campos *et al.*, 2002; Ruegg *et al.*, 2009; Madariaga *et al.*, 2010), but the timing of a future subduction earthquake in New Zealand is much less certain. We can say is that the southern North Island appears to have the potential to experience earthquakes of magnitude 8.2–8.7 and the locked “patch” lies not beneath the ocean as in most comparable settings elsewhere, but directly beneath the land and therefore closer to centres of population when it breaks.

Assuring life safety by minimising the risk of collapse is the objective of both modern Chilean and New Zealand engineering design and construction. Although some engineered buildings in Chile and New Zealand did collapse during the earthquakes of 2010 and 2011, respectively, most achieved the life-safety objective. Restoration of essential services in Chile as in Canterbury, predictably, was faster for above-ground services than for assets underground – the latter more severely affected by liquefaction and ground deformation (Figure 9.2). However, as the citizens of both communities have witnessed many modern buildings and

facilities suffered damage to non-structural components, including suspended ceilings, internal partition walls and exterior claddings, glazing and building services of many types. Damage to these elements has rendered many buildings unusable, contributing more than any other factor to severe economic and social disruption.

The Chile and New Zealand earthquakes of the past year, although very different in size and geological setting, have shown that the economic and social consequences of damage are severe. Current regulations in Chile and New Zealand include standards for the performance of these components, but the effectiveness of these provisions needs review. Partial damage to buildings significantly influences the cost and pace of post-earthquake recovery, highlighting the need for a more strategic dialogue between building owners, engineers and regulators about their expectations of building performance and protection. There are substantial benefits to taking precautions to reduce such damage whereas the potential cost of not doing so extends beyond material losses to the denial of access and potentially far-reaching interruption to civic life.

## 10. ACKNOWLEDGEMENTS

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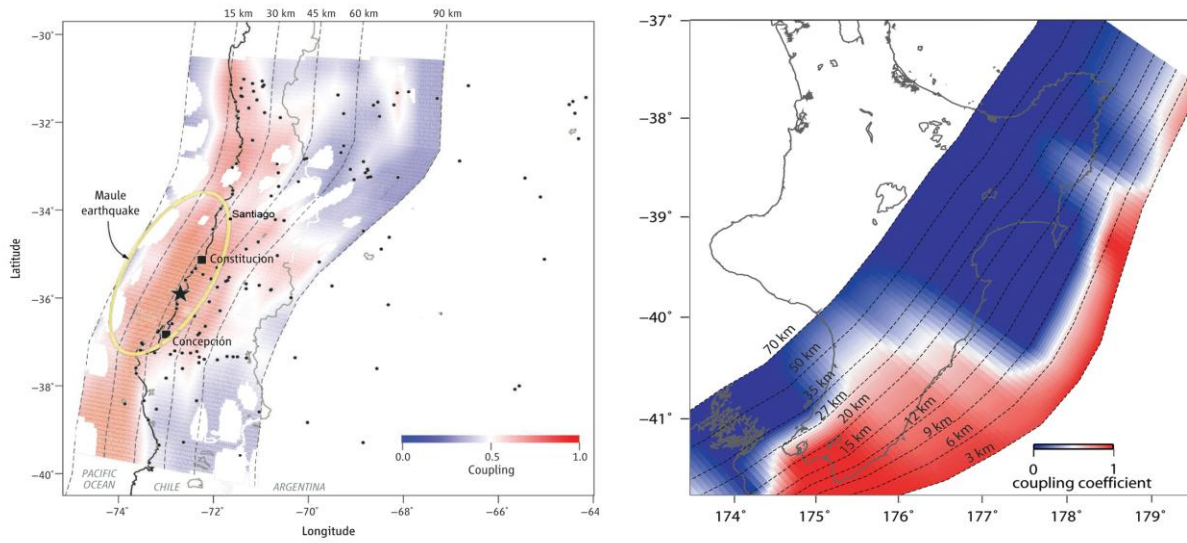


Figure 9.1: Distribution of tectonic plate locking on the Chilean (a) and New Zealand (b) plate boundaries, respectively, inferred from elastic strain rates as measured by GPS networks. The rupture area of the 2010 Chile earthquake is indicated by the yellow ellipse (Madariaga et al., 2010). The timing of a future subduction fault rupture in New Zealand is unknown, but the southern portion of the Hikurangi margin has the potential to generate earthquakes of magnitude 8.2-8.7 (Wallace et al. 2009).

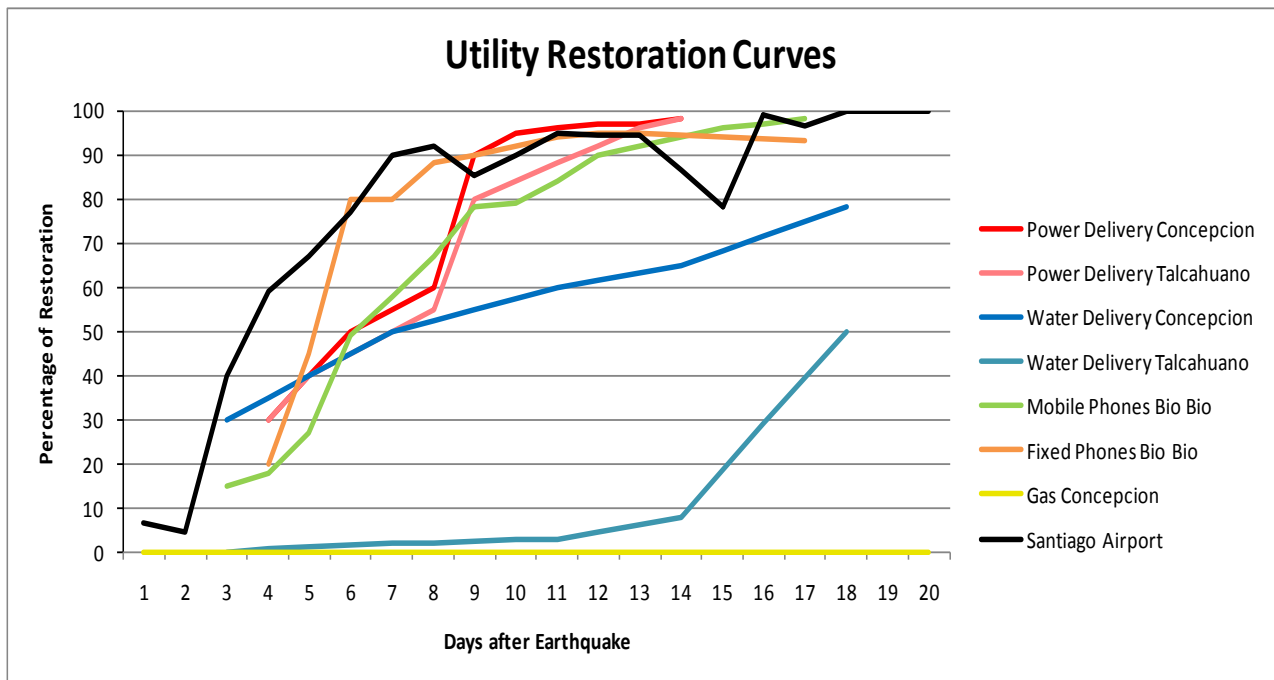


Figure 9.2: Curves showing length of time required to restore services for various utilities (Modified from ASCE TCLEE web report and others).

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