Learning from Earthquakes

The M_w 8.8 Chile Earthquake of February 27, 2010

From March 6th to April 13th, 2010, a team organized by EERI investigated the effects of the Chile earthquake. The team was assisted locally by professors and students of the Pontificia Universidad Católica de Chile, the Universidad de Chile, and the Universidad Técnica Federico Santa María. GEER (Geo-engineering Extreme Events Reconnaissance) contributed geosciences, geology, and geotechnical engineering findings. The Technical Council on Lifeline Earthquake Engineering (TCLEE) contributed a report based on its reconnaissance of April 10-17. A complete list of team members begins on page 19.

The research, publication, and distribution of this report were funded by the EERI Learning from Earthquakes project, under grant #CMMI-0758529 from the National Science Foundation. Additional support was provided by the Pacific Earthquake Engineering Research Center, Federal Highway Administration, American Society of Civil Engineers, and the host organizations of participating individuals.

Introduction

On Saturday, February 27, 2010, at 03:34 a.m. local time (06:34:14 UTC), an M_w 8.8 earthquake struck the central south region of Chile, affecting an area with a population exceeding eight million people, including 6.1M, 0.8M, and 0.9M in the urban areas around Santiago, Valparaíso/Viña del Mar, and Concepción, respectively. Figure 1 shows the location of the main shock and aftershocks relative to major cities. In the region of strongest ground shaking, ground accelerations exceeded 0.05g for over 120 s. Coastal locations were affected by both ground shaking and tsunami. Over 12 million people were estimated to have experienced intensity VII or stronger shaking, about 72% of the total population of the country, including five of Chile's ten largest cities (USGS PAGER).

As of May 2010, the number of confirmed deaths stood at 521, with 56 persons still missing (Ministry of Interior, 2010). The earthquake and tsunami destroyed over 81,000 dwelling units and caused major damage to another 109,000 (Ministry of Housing and Urban Development, 2010). According to unconfirmed estimates, 50 multi-story reinforced concrete buildings were severely damaged, and four collapsed partially or totally. The earthquake caused damage to highways, railroads, ports, and airports due to ground shaking and liquefaction. The earthquake was followed by a blackout that affected most of the population, with power outages affecting selected regions for days. Estimates of economic damage are around $30 billion.

According to the USGS (2010), the earthquake epicenter was in a zone where the Nazca plate is being subducted downward and eastward beneath the South American plate. The earthquake occurred as thrust faulting on the interface between the two plates, with an epicenter at 35.909°S, 72.733°W (just off the coast 105 km NNE of Concepción) and a focal depth of 35 km. The estimated dimensions of the rupture zone were 500 km long by 100 km wide. The earthquake struck in an area that had been identified as a seismic gap, with projected worst case potential to produce an earthquake of M_w 8.0-8.5 (Ruegg et al., 2009). The rupture zone extended beyond the northern and southern boundaries of the gap, overlapping extensive zones already ruptured in 1985 and 1960. In the first month following the main shock, there were 1300 aftershocks of M_w 4 or greater, with 19 in the range M_w 6.0-6.9.

Tectonic Setting and Geologic Aspects

South-central Chile is a seismically active area with a convergence of nearly 70 mm/yr, almost twice that of the Cascadia subduction zone. Large-magnitude earthquakes struck along the 1500 km-long coastline in 1835, 1906, 1928, 1960, 1985, and 2010 (Cisternas et al., 2005). Tectonic deformation resulting from the February 27th quake played a substantial role in the observed damage. Ground shaking and surface effects were observed

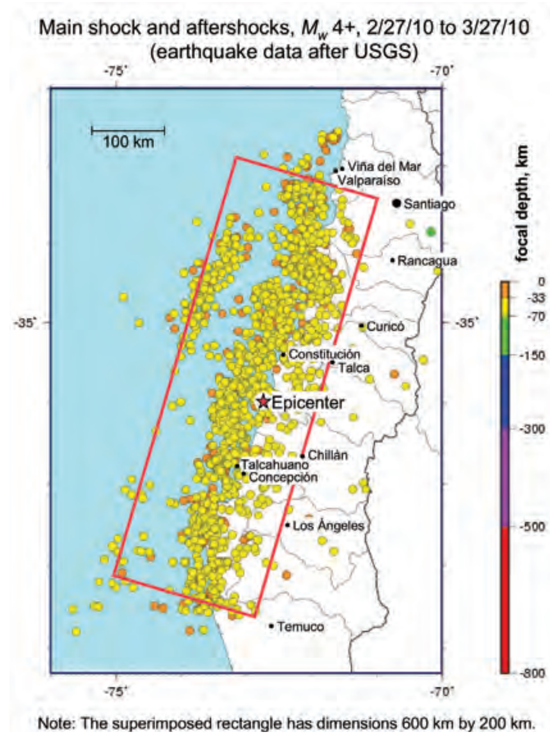

***Figure 1.** Main shock and aftershocks of M_w 4 and larger between 2/27/10 and 3/26/10 (USGS).*

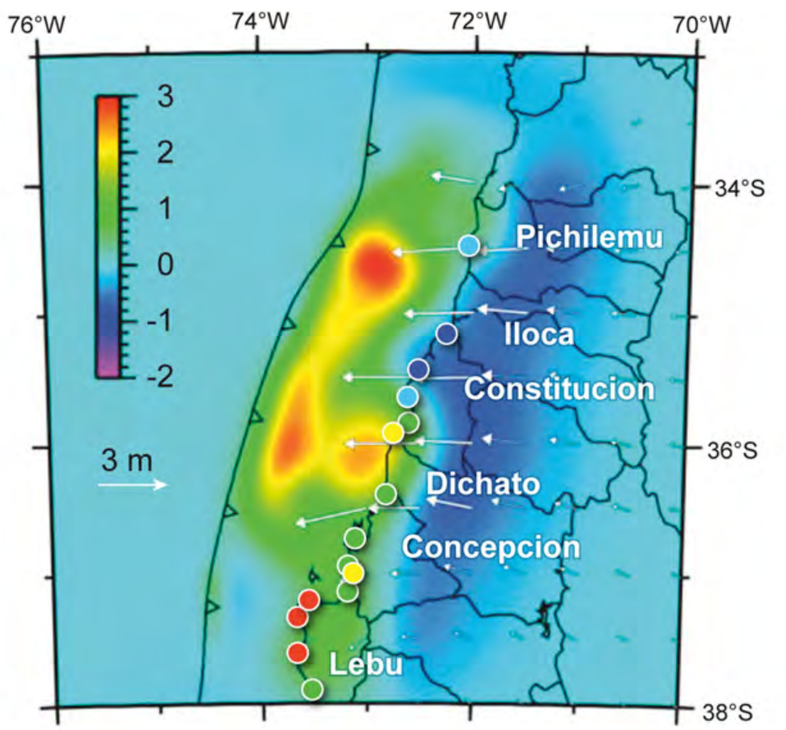

Figure 2. *Model of estimated surface deformation (after K. Wang, 2010, personal communication), overlain by initial field estimates of coastal uplift (GEER, 2010).*

over an area more than 100 km wide and 600 km long, from Valparaíso in the north to Tirúa in the south. This is equivalent to the entire coastline of Washington and Oregon.

In south-central Chile, regional geologic characteristics are largely controlled by long-term aseismic surface deformation, punctuated by sudden, coseismic coastal uplift and inland subsidence. These influence the pattern of ground motions and tsunami runup, and hence earthquake damage. The February 27 earthquake produced both uplift and subsidence along the coastline (Figure 2), and the variable pattern of deformation may have affected tsunami impacts on coastal communities.

Reconnaissance-based estimates of deformation (GEER, 2010) support initial models of surface deformation. In the south, the Arauco Peninsula was uplifted and tilted gently eastward, with at least 2 m of coastal uplift on Isla Santa Maria and near the town of Lebu. The uplift affected harbor facilities (Figure 3), produced an emergent marine platform, and exposed the tidal habitat zone. In the central part of the rupture zone, coastal subsidence over a distance of about 50 km between the towns of Constitución and Bucalemu resulted in drowned tidal flats and local areas of significant tsunami erosion. To the north, from about the town of Pichilemu to Valparaíso, there was little or no obvious uplift/subsidence. The areas of coastal subsidence were exposed to substantial tsunami runup and scour, as well as wave damage, whereas areas of substantial uplift generally had relatively little damage from tsunami waves. However, in coastal areas close to the epicenter with only moderate uplift (e.g., Concepción and Dichato), there was substantial damage related to both strong ground motions and tsunami runup.

Strong Motion

The main shock of the earthquake was recorded by at least 15 strong motion instruments in the area bounded by the cities of Santiago, Viña del Mar, Angol, and Concepción. At the station nearest to the epicenter, Cauquenes city, the accelerometer maximum 1g range was exceeded. Several of the recording instruments are analog, so processing is slow and still underway. Some of the digital instruments have been processed and reported in Boroschek et al. (2010) and National

Figure 3. *Fishing boats stranded within uplifted harbor of Lebu; uplift of 1.8 +/- 0.2 m in this area (photo: GEER, 2010).*

Table 1. Preliminary Processed Records Maximum Accelerations
(from Boroschek et al., 2010 and DGF 2010)

Station	Maximum Horizontal Acceleration (g)	Maximum Vertical Acceleration (g)
Santiago Universidad de Chile	0.17	0.14
Santiago Elevated Train Station Mirador	0.24	0.13
Santiago CRS MAIPU	0.56	0.24
Santiago Hosp. Tisne	0.30	0.28
Santiago Hosp. Sotero de Río	0.27	0.13
Santiago Cerro Calán	0.23	0.11
Santiago Campus Antumapu	0.27	0.17
El Roble Hill	0.19	0.11
Viña del Mar (Marga Marga)	0.35	0.26
Viña del Mar (Downtown)	0.33	0.19
Curico Hospital	0.47	0.20
Concepción Colegio San Pedro	0.65	0.58
Valdivia Hospital	0.14	0.05

Seismological Service (2010); additional records from research and private institutions have not been reported yet. Table 1 summarizes the known peak accelerations. The records show two to three minutes of vibrations (Figure 4). Shaking higher than 0.05g lasted more than 60 s in most of the records, and more than 120 s in Concepción area records.

Elastic response spectra of several records are higher than elastic design demands from the Chilean seismic design code NCh433; however, displacement spectra demands are in general lower than those required in the National Base Isolation Building Code NCh2745. Some records show important contributions to total signal energy from periods higher than 1 s. This behavior could be related to source or local soil conditions. Soil conditions on several stations are known only for the first 10 m, so further studies are required.

Geotechnical Effects

Local Site Effects. Damage patterns observed in Chile suggest local site effects were important. For example, Santiago is located on an alluvial sediment-filled basin surrounded by the main and coastal ranges of the Andes. Localized damage was observed along the Americo Vespucio Norte ring road, where four structurally similar overpass bridges exhibited markedly different performance: two collapsed while the other two had only minor damage. Another example of local site effects in Santiago was the severe structural damage of high-rise buildings observed at Ciudad Empresarial, a recently constructed business park founded on deep silty/clay sediments. Published data show that the fundamental periods of soil profiles in the area approximately match the fundamental resonant periods of the damaged structures there. The cities of Viña del Mar and Talca, founded on marine and alluvial deposits, suffered extensive damage during the earthquake. Concepción is founded on a sedimentary valley, and the extensive damage there was associated with site or basin effects. Among seven distinct zones in the city where buildings or bridges collapsed catastrophically, six were parallel to the La Pólvora fault, which defines the northwest edge of the basin.

Buildings. Liquefaction-induced ground deformations affected the seismic performance of several modern buildings. At a recently constructed hospital in Curanilahue, with ten structurally isolated wings ranging in height from one to six stories, individual wings underwent differential settlement and rotation due to extensive liquefaction. Four 8-story condominium buildings located in Concepción on a site filled with compacted sand were damaged by liquefaction-induced permanent ground movement and by strong shaking. The Riesco building at this site underwent 30 cm of dif-

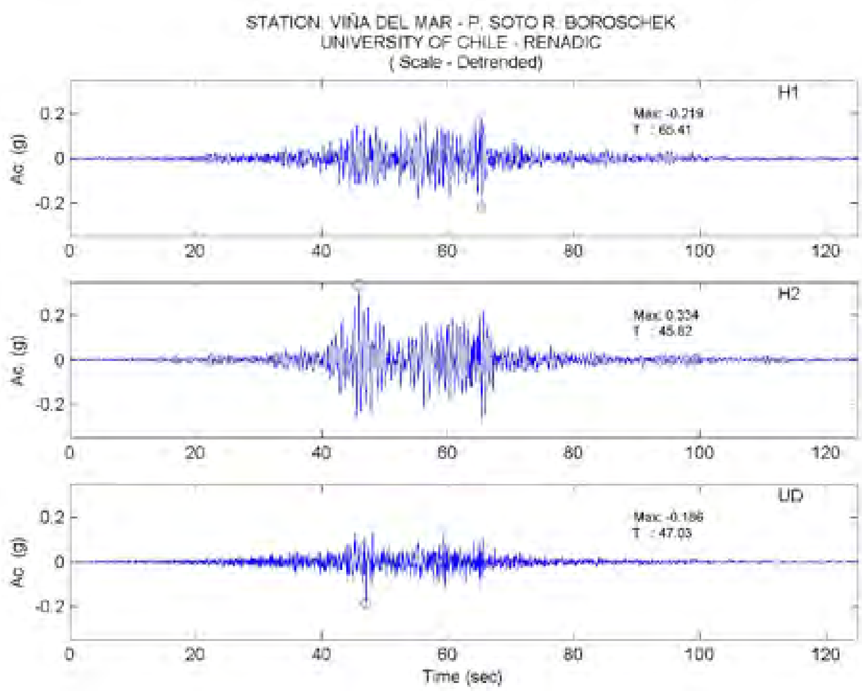

Figure 4. *Viña del Mar downtown area earthquake records. This same station recorded the 1985 Central Chile Earthquake. NS and EW are nominal coordinates.*

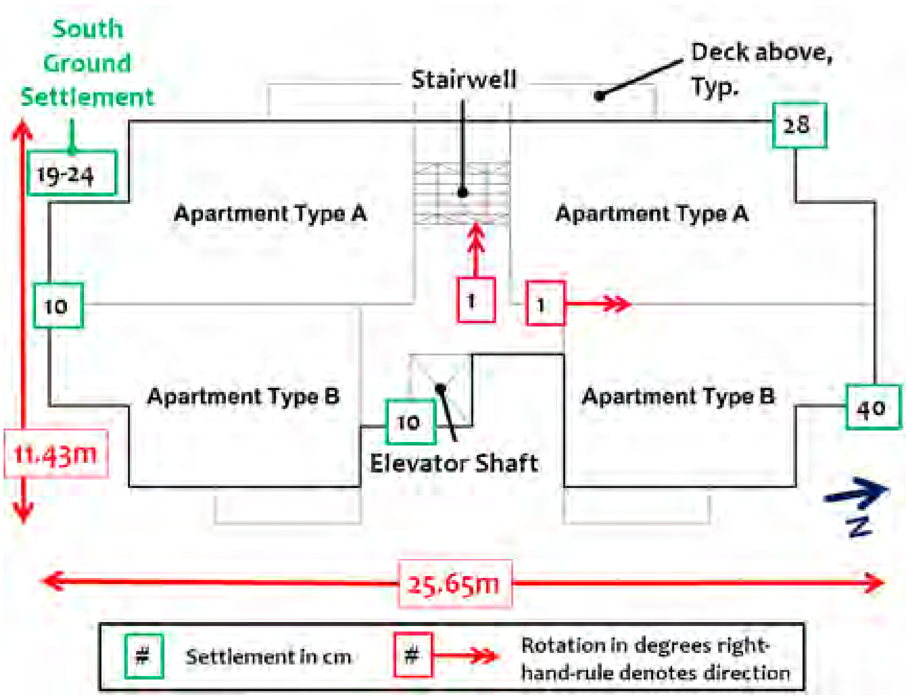

Figure 5. *Schematic plan view of the Riesco building in Concepción (GEER, 2010).*

ferential settlement across its foundation and 1 degree tilt in the north side of the building (Figure 5). As a result of the uneven foundation settlement and rotation, excessive internal deformations were imposed on the coupling beams in the superstructure. Several homes in northern Concepción were torn apart by translational ground movement.

Ports. Ports are essential facilities for the Chilean economy, as they carry more than 90% of the country's imports and exports. There was significant damage due to liquefaction and lateral spreading, notably at Valparaíso and Coronel. Figure 6 shows cracking of asphalt pavement at Coronel with lateral ground extension in excess of 1.2 m.

Bridges and Roads. Liquefaction affected transportation systems most significantly along the coast. For example, all four bridges crossing the Bio-Bio River near Concepción were damaged to varying degrees by liquefaction-induced ground failure. The Llacolen Bridge, built in 2000, suffered deck unseating due to lateral spreading at its north approach. The Juan Pablo II Bridge, built in 1974, was closed due to column shear failure induced by lateral spreading at the approach, as well as interior pier settlement in excess of 0.5 m due to liquefaction. (See also Transportation Systems below and Figure 26). At the Bio-Bio Bridge, built in 1937 and closed in 2002 to all but pedestrian traffic, there was lateral spreading at the east approach and several spans collapsed in the middle. The Bio-Bio Railroad Bridge, built in 1889 and retrofitted in 2005, also suffered damage associated with lateral spreading, including lateral pile movement and misalignment of the rails. Damage from lateral spreading was also observed at the La Mochita Bridge in Concepción (significant transverse movement), the Tubul Bridge in Tubul (collapse), and the Pulen and Pataqual bridges near Hualqui (moderate cracking and distortion). The Mataquito Bridge, built in 2008 near Iloca, performed well, although lateral spreading was observed at both abutments, and up to 0.5 m of liquefaction-induced settlement was measured at one abutment.

Localized ground failures also had widespread impact on highways throughout the region affected by the earthquake. Route 160 in Lota along the coast was closed in both directions due to embankment slope failures (Figure 7). Several ground failures were observed inland along the main north-south highway, Route 5, often resulting in the closure of either northbound or southbound lanes (e.g., near Copihue, Parral,

Figure 6. *Liquefaction and lateral spreading-induced damage at the Port of Coronel (photo: GEER, 2010).*

Figure 7. *Slope failure on Route 160 in Lota (photo: GEER 2010).*

and Paine). These failures were often associated with lowland crossings or under-highway culverts.

Earthen Structures. The performance of earthen structures — dams, levees, mine tailings dams, and retaining structures — was good overall. The earthquake struck near the end of the dry season in Chile, when reservoir levels are low. A small number of earth structures did exhibit adverse effects. For example, Coihueco Dam, which is a 31-m-high zoned earth fill dam, had several scarps along its upstream crest, as well as bulging along the upstream toe. The most significant failure of an earth structure was at the Las Palmas Tailings Impoundment, where liquefaction resulted in a flow failure of as much as 100,000 m^3 of retained tailings a distance of up to 0.5 km and caused four casualties (Figure 8). Another interesting failure was in a 7-m-high earth levee constructed with a silty-sandy gravel with cobbles near Colbún. While this section of levee showed no signs of distress after both the February 27 event and a M_w 6.9 aftershock on March 11, it subsequently failed on March 13.

The Tsunami

The earthquake produced a tsunami that caused major damage locally over 500 km of coastline, from Tirúa to Pichilemu, and at the Juan Fernandez Islands about 600 km off the coast. Around the Pacific, the tsunami was recorded at over 150 locations, triggering tsunami alerts (Warnings/Advisories) in 54 countries and territories. Post-event field investigation International Tsunami Survey Teams (ITST) were coordinated by UNESCO and the International Tsunami Information Center (ITIC, 2010).

A conspicuous feature of the Chilean tsunami was its extreme variability in height, destructiveness, and wave arrival times (Table 2). Local tsunami water height and arrival times were influenced by bathymetry, coastal topography, aspect, fault slip, and localized subsidence and uplift due to the earthquake. The first tsunami surges generally arrived less than 30 minutes after the earthquake; in most areas, eye witnesses reported three or four distinct surges. The third or the fourth were typically the largest, arriving between 90 minutes and four hours after the earthquake. The highest water levels recorded by ITST groups were generally in the 10–12 m range, excepting splash values. Tidal variations of about 1.6 m from rise to fall in 20-30 minutes intervals were still observed in the Valparaíso area 7-8 hours after the earthquake, revealing the intense excitation the Pacific Ocean experienced.

Tsunami damage to structures resulted from hydrodynamic loading on structural elements, impact loading from floating debris, and scour around foundations, especially during drawdown. Timber-framed homes and unreinforced or poorly reinforced masonry structures were particularly vulnerable (Figure 9). In Dichato, 1500 homes were

Figure 8. *Upper scarp of Failed Tailings Impoundment (photo: GEER 2010).*

Table 2. Water Heights and Wave Arrival Times

Community	Water Height meters[1]	Approximate Wave Arrival Time[2] 1st	2nd	3rd	4th
Curanipe	6 - 9				6:30 - 7:00
Constitución	6.9 - 11.2, 26*	3:50	4:17	4:50	5:20
Dichato	3.6 - 9.4	4:00	5:00		7:30
Iloca	4 - 8.2	4:00	4:25		
Juan Fernandez	5	4:25	4:40		
Pellehue	7.2 - 9.3	4:15			7:30
Pichilemu	4	3:50	4:20		
San Antonio	2.5 - 3.4	3:50	4:20		
Talcahuano	3.3 - 6.3	3:54	5:30	6:00	6:40
Valparaíso	2.6	4:00	4:50	5:20	6:00

[1] Compilation of preliminary water heights from NGDC (2010), ITST and EERI teams
[2] Based on eyewitness accounts from ITST teams and El Mercurio (2010)
** Splash estimate*

destroyed, primarily because of hydrodynamic loads, though debris generated by failed homes may have progressively contributed to the loading. Light-framed buildings were destroyed in many other coastal towns. Reinforced concrete buildings, on the other hand, performed very well structurally, even when inundation reached well above the second floor level.

Bridges on coastal highways also sustained tsunami damage such as the lateral distortion of the superstructure of the Pichibudi Bridge just north of Iloca, the undermining of several piers due to scour and the puncture of steel pile bents by floating debris in the Cardenal Silva Henriquez Bridge across the Maule River at Constitución.

In Talcahuano, nonstructural damage was widespread; almost all exterior enclosures and contents of commercial buildings and industrial warehouses along the shorefront were damaged by the hydrodynamic loading of the flooding and debris field, and the commercial fishing facilities along the wharf were also rendered inoperable. Debris impact, particularly in the form of fishing vessels, shipping containers, and trucks, caused damage to masonry and steel-framed harbor buildings, though reinforced concrete structures were generally able to withstand the battering (Figure 10). The piers at the Naval Base at Talcahuano were also damaged due to uplifted large naval ships and barges.

Scouring of shallow foundations caused a number of buildings to collapse (Figure 11). Sheetpile wharfs in Talcahuano Harbor collapsed or were damaged by soil failure induced by tsunami inundation and drawdown. Elevated pore pressures led to fluidization of backfill during tsunami inundation and drawdown, causing severe scour that damaged sheetpile wharf structures, machinery with shallow foundations, and soil-supported pavements. Eyewitness reports from dockworkers indicated that the majority of damage was caused by the tsunami. According to Ministry of Interior data in May 2010, 124 of the 521 identified casualties and missing were attributed to the tsunami (Forensic Medical Service, 2010). With the notable exception of Constitución (see below), few coastal residents died in the tsunami, because of a high level of tsunami awareness. Older residents had personal experience of the 1960 earthquake and tsunami, and many coastal residents recognized ground shaking as the warning. Many towns had posted tsunami hazard zone signs and/or tsunami evacuation zone signs (Figure 12). In Chile, all schools are required to prepare for local natural hazards, and the coastal schools had robust tsunami awareness and education programs.

Most vulnerable were unaware transient populations. The single largest loss of life from either ground shaking or inundation was in Constitución, where numerous people died on La Isla Orrego in the River Maule (*LA Times*, 2010). The island was accessible only by boat, had no high ground, and was an informal campground packed on the weekend of February 27. In other areas, campgrounds were also filled. Campers in Pellehue and Curanipe accounted for large numbers of fatalities. There were no education programs targeting tourists or other transient populations.

***Figure 9.** Wood building on left in Dichato was transported from across street and collided with the concrete frame building on the right. Arrow shows water height (photo: L. Dengler).*

Figure 10. *Talcahuano Harbor 3 days after the tsunami (photo: Intl. Federation of Red Cross Red Crescent Societies). Shipping containers were originally stacked in the area of the red ellipse and displaced up to 300 m in the direction of the arrow.*

There were difficulties with Chile's tsunami warning system. An initial warning was cancelled by the Navy's Hydrographic and Oceanographic Services and announced on the radio by Chile's president. In Chilean coastal communities, where most people recognized natural warning signs and there was little time between the earthquake and tsunami, the failure of the official warning system may have had little impact, although there are some reported cases of people returning to the coast after hearing of the cancellation. In the Juan Fernandez Islands, 600 km off the coast, the lack of timely warnings may have hindered evacuations.

Figure 11. *This concrete frame and confined masonry building in Dichato survived the hydrodynamic loads, but suffered substantial foundation scour (photo: G. Chock).*

Fortunately a 12-year-old girl who felt the earthquake rang a village bell, alerting most of the residents on Robinson Crusoe Island (*The Independent*, 2010).

Buildings

Earthquake shaking caused extensive damage to many non-engineered and engineered buildings throughout the affected area. The team focused on concrete, masonry, and adobe construction, as this constitutes the vast majority of buildings. Some damage to steel buildings also was observed, but is not reported here.

The region contains a large number of older houses, churches, and other buildings constructed of adobe or unreinforced masonry. Seismic resistance typically is provided by walls located around the perimeter and, to a lesser extent, at the interior. Absence of reinforcement and weak connections between adjoining walls apparently led to the collapse of walls and roofs in many buildings, contributing to some human fatalities. In addition, delamination of exterior stucco, while not jeopardizing the structural system, created the appearance of significant damage in many other buildings. Damage was especially severe between latitudes 34.5° and 36.5°, a length of 240 km (Astroza et al., 2010). Figure 13 shows a typical street scene from Talca. Historic churches were particularly hard hit, with extensive damage observed from Santiago to Concepción.

Confined masonry construction is also widely used for buildings one to four stories tall (Figure 14). Exterior walls of clay bricks are first constructed on a concrete foundation and then reinforced concrete confining elements are cast around the brick walls, forming a tight bond between the masonry and concrete elements. These buildings generally performed very well; typical damage (where observed) included diagonal cracking of masonry walls and

Figure 12. *Tsunami evacuation sign, Curanipe (photo: N. Graehl).*

wall failure due to lack of confining elements around openings or poor quality of the confinements.

The vast majority of mid- to high-rise buildings in Chile are constructed of reinforced concrete. Most of these rely on structural walls to resist both gravity and earthquake loads; some more recent construction uses a dual system of walls and frames. A typical high-rise plan has corridor walls centered on the longitudinal axis, with transverse walls framing from the corridor to the building exterior. Typical ratios of wall to floor areas are relatively high compared with concrete building construction in the U.S. In 1996, Chile adopted a seismic code with analysis procedures similar to those in UBC-97, but there are no prohibitions or penalties related to vertical or horizontal system irregularities. NCh433-1996 also enforces provisions of ACI 318-95; however, in light of good building performance in the March 1985 earthquake, it was not required to provide closely spaced transverse reinforcement around wall vertical boundary bars. Starting in 2008, the new Chilean Reinforced Concrete Code does require use of boundary elements. An apparent trend is to use thinner walls in recent years than in the past.

The team observed severe damage to 31 concrete wall buildings (10-26 stories) in or around Santiago, Viña del Mar, Chillán, and Concepción. In Viña del Mar, damage was generally concentrated in the alluvial plain directly north of the Marga-Marga River, where a majority of the taller buildings are located. Some buildings damaged in the 1985 earthquake (and repaired) were again seriously damaged (e.g., Festival and Acapulco); however, a majority of damage was concentrated in newer buildings.

Figure 13. *Street in Talca (photo: J. Moehle).*

Figure 15 shows typical damage to a transverse wall in the first story of a ten-story building in Viña del Mar. Note the setback in the wall profile at this level, provided mainly to accommodate automobile access to parking spaces. This condition was observed in several buildings; in buildings with subterranean parking, this damage was likely in the first level below grade.

Figure 16 shows a failed wall from a subterranean level of a 12-story building in which large steel pipe columns were being used to raise the building to enable repairs. Given the wide spacing of transverse reinforcement, there was little bearing section remaining in the thin wall and the entire wall section buckled laterally. In this example the longitudinal bars buckled without fracture; in many other examples the longitudinal bars were fractured. It was reported that, even though not required by the local building code, some engineers used transverse reinforcement conforming to the ACI Building Code. The team did not observe that type of reinforcement in any damaged buildings.

Coupling beams over doorways along corridor walls are typically reinforced with small-diameter hoops at relatively large spacing (20 cm); many buildings had damage to these beams. Some buildings omitted the coupling beams; in many cases, damage resulted from the slab acting as a coupling element. There were several examples of doors becoming jammed because of permanent offsets in the walls adjacent to the opening. The team also observed spalled cover over lap splices of wall boundary reinforcement.

Several of the severely damaged mid- to high-rise buildings had permanent offsets at the roof, apparently due to subsidence of walls, raising questions about repairability. Four concrete buildings collapsed

Figure 14. Engineered confined masonry apartment building, showing confining elements at boundaries of walls and openings (photo: M. Astroza).

completely or partially. Two of these were nearly identical, proximate, five-story buildings in Maipú, Santiago. These buildings had four stories of condominium units atop a first-story parking level with a highly irregular wall layout. Wall failure likely contributed to the collapses.

A third collapsed building was the 15-story Alto Río condominium in Concepción (Figure 17). The team was unable to examine closely the side of the building toward which it collapsed, but the structural drawings indicate that concrete walls on the façade were discontinued, and the wall length was decreased in the first story on the side toward which the building collapsed. The building apparently rotated about its corridor walls as it collapsed, leading to tension failures of the transverse walls on the other side (the side from which the photo was taken). Some of the wall vertical reinforcement fractured and some lap splices failed on the tension side.

The recently completed 23-story O'Higgins 241 office tower in Concepción suffered partial story collapses at levels 10, 14, and 18, each coincident with a framing setback (Figure 18). The perforated shear walls on the east face (shown) and south face showed damage to both wall piers and spandrels. Exterior north and west faces appeared undamaged.

Nonstructural Components and Systems

There was extensive nonstructural damage in practically all types of buildings — residential, commercial, and industrial. Commonly observed was damage to glazing, ceilings, fire sprinkler systems, piping systems, elevators, partitions, air handling units, and cable trays (Figure 19). The widespread nonstructural damage caused significant economic loss and major disruption to the normal functioning of Chilean society.

With few exceptions (e.g., some newer hospitals), Chilean practice on seismic anchoring/bracing of nonstructural components lags considerably behind earthquake-resistant design practice for structural systems. Although Section 8 of the Chilean seismic code (NCh 433.Of96) includes provisions for nonstructural components, these are usually not enforced unless requested by building owners, as in newer hospital construction. The state of practice is similar to that for buildings constructed in the early 1970s in California or typical current practice in other U.S. regions of moderate seismicity. As with U.S. practice, for most buildings it is not clear who is responsible for the design, installation, and inspection of seismic anchoring and bracing of nonstructural components.

Nonstructural damage resulted in the closure of the international airports in Santiago (see Figure 20) and Concepción, which together handle more than two thirds of the air traffic in Chile. The cost of the earthquake to

Figure 15. Wall damage, Viña del Mar (photo: P. Bonelli).

Figure 16. *Wall damage, Santiago. Note the 90-degree bends on the transverse reinforcement (photo: J. Wallace).*

LAN Airlines, the national airline in Chile, was approximately $25 million in lost passenger traffic alone.

Of the 130 public hospitals in regions affected by the earthquake, 62% suffered nonstructural damage requiring repairs. Most of the economic loss, closures, and evacuations in hospitals are attributed to nonstructural damage. For example, of the hospitals that were partially or completely closed as a result of the earthquake, 83% lost some or all functionality exclusively due to nonstructural damage (they suffered no structural damage).

Santiago's 131 emergency call center (analogous to 911 in the U.S.), located in the uppermost level of the Posta Central building, suffered severe nonstructural damage and could not operate following the earthquake. Nonstructural damage also caused significant losses and disruption to industries associated with paper, wine, grain, and fruit.

This earthquake illustrates the importance of improving seismic performance of nonstructural components, the failure of which can lead to injuries, loss of functionality, and substantial economic losses. This is especially important for critical facilities such as hospitals, airports, and water distribution systems.

Hospitals and Health Care

The 130 hospitals in the six regions affected by the earthquake account for 71% of all public hospitals in Chile. The Chilean Ministry of Health (MINSAL) found that of these, four hospitals became uninhabitable, twelve had greater than 75% loss of function, eight were operating only partially after the main shock, and 62% needed repairs or replacement. Of the beds in public hospitals, 18% continued to be out of service one month after the earthquake. MINSAL estimates the damage at $2.8B, and expects the replacement of severely damaged hospitals to take three to four years.

The hospital operability study was focused on the Bio-Bio province of Chile. The only hospital in the chosen study area with structural damage is the Victor Rios Ruiz Hospital of Los Angeles. In one of the newer buildings of this hospital, braced by concrete frames with shear walls, the penthouse was severely racked due to torsion, and steel roof trusses buckled. Two other buildings, circa 2005, had damage to some columns, slight cracking on the shear walls, and collapsed in-fill walls. This wall failure caused damage to nearby

Figure 17. *Collapsed Alto Río tower showing underside (photo: J. Maffei).*

Figure 18. *O'Higgins 241 office tower (photo: E. Miranda).*

distilled water tanks, subsequently shutting down half of the hospital surgical ward, located on the floor below, due to water damage. The saw no evidence of structural damage in any of the one-story hospitals of the Bio-Bio province built after the 1960 earthquake.

Although structural damage was minimal in hospitals, most suffered nonstructural damage, and frequently, loss of utilities. All hospitals in the study area lost municipal electrical power and communication for several days, and 71% lost their municipal water supplies. All hospitals were equipped with backup power and water supplies, but such redundancy was not present in their communication system, creating enormous difficulties for aid coordination.

Additionally, most hospitals reported damage to their suspended ceilings, cracking of the plaster over brick walls, and partition damage. The collapse of ceilings and associated light fixtures and mechanical grills (Figure 21a) discomfited occupants and caused unsanitary conditions that led to many evacuations.

A few hospitals also had moderate water damage from pipe failures. Most buildings that required evacuation also lost use of elevators — due to lack of power or failure of the counterweight rails — forcing staff to carry patients down rubble-strewn stairs. However, the only reported patient casualties were due to heart attacks.

Although no hospital lost the capacity to provide all regular service, all but one saw reductions in multiple services for up to seven days. Radiologic and laboratory services were most affected by earthquake damage. In terms of patient care, the largest deficit was due to the loss of 54% of beds in the Los Angeles Hospital. With hospital non-clinical services, the most frequent interruption was due to the loss of patient medical records (Figure 21b) in collapsed and tipped file management systems.

The team visited three seismically isolated hospital buildings in Santiago; none was damaged other than at joints with adjacent buildings or other structures. In two cases, immediately adjacent fixed-base buildings had moderate nonstructural damage.

Lifelines

The TCLEE reconnaissance team examined earthquake impacts to electric power, telecommunication, water and wastewater, gas and liquid fuel, and other lifelines (not presented here), and evaluated lifeline interdependence and resilience. The study of lifeline resiliency must continue with a focus on cost-effective preparedness and loss reduction for lifeline service providers.

Electric Power. The transmission network performed reasonably well and was ready to provide power 24 hours after the main shock. The long, narrow configuration of the system — dictated by the shape of the country and the topography of the land — limits transmission line route dispersion and system redundancy. While much of the equipment is the same as that found in the United States, Chile makes extensive use of pantograph disconnect switches and candlestick

Figure 19. *Nonstructural damage in the Talca Supreme Court building constructed in 2003 (photo: E. Miranda).*

live-tank circuit breakers, which are used sparingly in the western United States. There were more than 25 failures reported in these elements, but that represented only a small percentage of the inventory (Figure 22). The backbone 220 kV and 500 kV systems, which were designed with earthquake provisions, performed reasonably well overall. Lower voltage subtransmission systems near the coast, where there were higher levels of ground shaking, were damaged sporadically. The low-voltage distribution system was also affected by collapsed buildings and damaged poles. Two weeks after the earthquake, the distribution system service was restored.

***Figure 20**. Nonstructural damage at the Santiago International Airport terminal (photo: E. Miranda).*

Telecommunication. Both landline and wireless services were bedeviled by commercial power outages, equipment failures, building failures, and loss of reserve power in most distributed network facilities (base stations, small remote switches, and digital loop carrier [DLC] remote terminals). Only critical offices have backup power generators, with the majority of cell sites and remote offices relying on battery reserve power; by about 6:30 a.m., most cell sites and remote sites ran out of power. Damage to roads and bridges made access to these sites difficult; additionally, many utilities that relied on wireless service found it difficult to dispatch maintenance crews in order to restore service. Both landline and wireless services were restored within seven days of the quake.

Water and Wastewater. Chilean water utility Essbio delivers potable water to urban areas, serving about 4 million people. The potable water systems include about 7,000 km of transmission and distribution pipe, of which 1,200 km are in the city of Concepción. By far the largest amount of damage to the various Essbio water systems was concentrated in Concepción and Talcahauno. Areas within 60 m (or so) of river banks often were affected by lateral spreading and settlement, and tsunami-related destruction to buildings and sea walls damaged buried water pipes. At the Concepción-area water treatment plant, there was severe damage to the raw water intake structure from both lateral spreading and ground shaking; internal damage to the four clarifiers (baffles, settlers and supporting elements); damage to suspended

***Figure 21.** (a) Ceiling collapse and nonstructural damage in Chilean hospital (photo: W. Holmes), and (b) tedious reorganization of medical records three weeks after the earthquake (photo: J. Mitrani-Reiser).*

ceilings (control room, water quality laboratory); toppling of control room computer monitors and computers; and toppling of water quality equipment and glassware from countertops. In the Concepción-area distribution system, there were 72 breaks or leaks to large diameter (500+ mm) welded steel pipes; as of April 12, 2010, about 3,000 repairs had been made to smaller diameter pipes, of which about 2/3 were for service laterals and 1/3 for pipe mains.

Over the past 50 years, the federal government of Chile has constructed nearly 2,000 small rural potable water systems country-wide, of which about 420 were in the areas of strong shaking. At least 73 of the elevated tanks completely collapsed (Figure 23).

There was heavy damage to wastewater systems, including treatment plants, large-diameter interceptor pipes, and small-diameter collector pipes. Due to the damage, there were direct discharges of sewage into rivers. Primary causes of damage were permanent ground deformations for pipes and inertial overloads to structures.

Gas and Liquid Fuel. Chile has two principal oil refineries, one west of Santiago and one in Concepción. Both refineries shut down (loss of power, need to appraise possible damage) with only minor, non-critical damage. The Aconcagua refinery near Santiago had minor damage and restarted ten days after the earthquake. At the Bio-Bio refinery near Concepción, the refractory in the heaters fell to the heater floors, and one of the two steel crude oil pipelines feeding into the refinery failed due to liquefaction and lateral spreading of beach sands. The gasoline and diesel for the service area of this refinery is currently being imported. It has been estimated that three to seven months will be required to bring the refinery to its operating capacity of 130,000 barrels per day.

Figure 22. *Damaged candlestick style live-tank circuit breakers (photo: TCLEE).*

Lifeline Interdependence and Resilience. Infrastructure interdependence among power, transportation, telecommunication and water systems increased their loss of functionality or delayed the restoration processes. This additional loss of functionality reduced regional resilience, and it was triggered by physical and cyber interaction among lifeline systems, as well as by co-location, and by relational and logistical coupling among infrastructures and institutional entities.

The early post-earthquake phase was characterized by uncertainty about road conditions and the absence of power. Blackouts impaired telecommunication system operation. Uncertainty about refinery shutdowns and fuel availability hampered water systems' operation of the undamaged and repaired portions of the network. Lack of telecommunications during the blackout phase also led to delays in assessing the damage and safety of the power

Figure 23. *Typical collapsed elevated small steel tank (constructed in 1999) (photo: TCLEE).*

distribution system. This phase had different durations in different regions, but for the Concepción area, it lasted about three days. The subsequent phase was characterized by the increasing availability of alternate transportation routes, restoration of power at the subtransmission levels, a steady recovery of telecommunications, water and gas, and improving power delivery to customers along main feeders and then laterals.

Although important underground, overhead, and surface level co-located infrastructure was observed in the field, in only a few instances were there interdependence-induced failures. These included telecommunication, gas, and water lines conveyed by collapsed or excessively displaced bridges at waterway crossings, electric train halts from power and telecommunication downed poles, rooftop telecommunication structure failures or interrupted operations at collapsed buildings, and power distribution overhead lines pulled down by collapsed facades or structures.

Most lifeline companies managed to avoid operational personnel shortages by supporting workers with food and water provisions, and by linking to relative search programs. However, the services of some companies, such as banks in dense urban areas, are not going to receive power and other utility services until demolition of tagged buildings takes place, despite having completed their own retrofit projects. Re-installation of utility infrastructure can interrupt their business for another three or four months. Further, the rate of lifeline restoration slowed down after a majority of customers were back on line, so the remaining residential and commercial users endured significant inconvenience and indirect losses.

Transportation Systems

Ground shaking and liquefaction damaged highways, railroads, ports, and airports as noted above. Highways and railroads between Concepción and Constitución also had substantial tsunami damage. The most serious damage occurred to roads and bridges. Of the nearly 12,000 highway bridges in Chile, approximately 200 were damaged. About 20 of these bridges had collapsed spans. Before the mid-1980s, the bridge design code in Chile was based on the provisions in the AASHTO Standard Specifications of that time, with a seismic design coefficient of 0.12. This coefficient was increased to 0.15 following the 1985 earthquake, and a modified version of Division I-A of the AASHTO Standard Specifications was adopted in 1998. The design coefficient was not, however, changed until 2001, when three seismic zones were introduced with PGAs of 0.2, 0.3, and 0.4g. Columns were required to be designed to the requirements for Performance Categories C and D of Division I-A.

Since the mid-1990s, a number of major highways have been constructed in Chile using design-build-and-operate contracts with entities known as concessions. Many of the bridges built by these concessions used precast, prestressed concrete girder superstructures without diaphragms or shear keys for transverse restraint. Vertical rods and hold-down ties were provided to prevent uplift, after high vertical ground accelerations were recorded during the 1985 earthquake. These rods and ties were largely ineffective in the transverse direction, and many spans slid sideways on their cap beams. This lack of restraint also allowed a number of two-span bridges to rotate about a vertical axis through the pier and slide off their abutments seats (Figure 24). In addition, several skewed spans with diaphragms and shear keys also rotated about a vertical axis and were unseated in their acute corners, due to insufficient support length (Figure 25). Straight bridges built before the concession era and those with cast-in-place diaphragms and concrete shear keys behaved well.

Despite higher-than-anticipated spectral accelerations, column damage was slight, perhaps because the lack of transverse restraint and insufficient support length allowed many superstructures to separate from their substructures, limiting the demand on the columns. Where this did not happen, column damage was more likely to occur, such as the shear failures of several columns under the approach span to

Figure 24. *Lateral movement of the superstructure of Las Mercedes Bridge across Route 5 near Rancagua, due to absence of end diaphragms and transverse shear keys. Note extreme deformation of vertical seismic bars and damaged curtain walls (photo: Ministerio de Obras Públicas).*

the Juan Pablo II Bridge across the Bio-Bio River in Concepción, apparently due to imposed displacements from liquefaction-induced lateral spreading (Figure 26). Other bridges across the Bio-Bio River also suffered damage from lateral spreading, as noted above under Geotechnical Effects.

The Ferrocarril del Pacífico S.A. (FEPASA) maintains tracks parallel to the Pan-American Highway (Route 5), and several areas of track and railway bridges were damaged due to soil movement. Several piers and bearings supporting the rail bridge at Chepe Hill across the Bio-Bio River in Concepción were damaged by lateral spreading. Tsunami damage was reported between Constitución and Talca; however, repairs were made quickly, and the railroads were used to help remove earthquake debris.

Damage to the major ports of Valparaíso and Concepción (Coronel) has been attributed to strong shaking and liquefaction-induced lateral spreading, rather than the tsunami. The San Antonio Port had been reconstructed between 1992 and 1997, and was undamaged. A new, seismically isolated wharf in Coronel (Figure 27), carrying two container cranes, was not damaged, whereas a neighboring conventional wharf of similar size had weld failures in some steel pile bents.

Industrial Facilities

The Chilean economy is heavily centered on minerals extraction, agricultural production, and forestry. The agricultural and wine production regions, stretching south from Santiago towards Valdivia, were affected by the earthquake, as were the paper and cellulose mills located in the areas from Constitución south. Steel mills, refineries, and cement and electricity plants in the Concepción area were also damaged, some seriously. The overall impression from the team is that modern industrial facilities designed to the recent NCh2369 seismic design code for industrial facilities performed well structurally; however, significant downtime and losses resulted from improperly anchored equipment and contents.

Wineries. Some older wineries with adobe walls and timber roofs or ribbed brick vaults sustained localized collapses. Modern warehouse structures were minimally damaged, mostly in the tension braces, but there was damage to steel fermentation tanks, barrel stacks, and bottle storage racks. One wine industry representative reported that more than 75% of total capital loss was from loss of wine from stainless steel tanks, with most of the remainder from damage to the tanks themselves. Local buckling of legged tanks in many cases led to subsidence or toppling that ruptured piping or valves, leading to loss of wine (Figure 28). Total wine losses were estimated at over 125M liters.

Cement Factories. The very large, modern Bio-Bio cement plant south of Curico (about 100km from the epicenter) suffered only minor damage to its installations, mostly in the form of fine shear cracks around some of its larger concrete silos, some minor buckling of steel braces near the top of its main bagging facility, and damage due to excessive movement of equipment. The Bio-Bio plant at Talcahuano apparently suffered more damage, but the team was unable to visit that installation.

Cellulose Plants. The large Arauco brown paper plant in Constitución had minimal structural damage from ground shaking, but much of the equipment was submerged and displaced from its original location by the tsunami. Water damage to the equipment controls systems was serious. Another Arauco cellulose plant at Nueva Aldea, near Chillán, appeared to have suffered no serious damage.

Power Plants. The team visited the 350 MW Santa Maria power plant under construction in Coronel, south of Concepción. The plant is about 60% complete and consists primarily of three very large braced steel frames. Damage was limited to portions of the structure that had not been finished or where there was seismic settlement under some foundations that were on spread footings.

Refineries and Steel Mills. The team was unable to enter either the

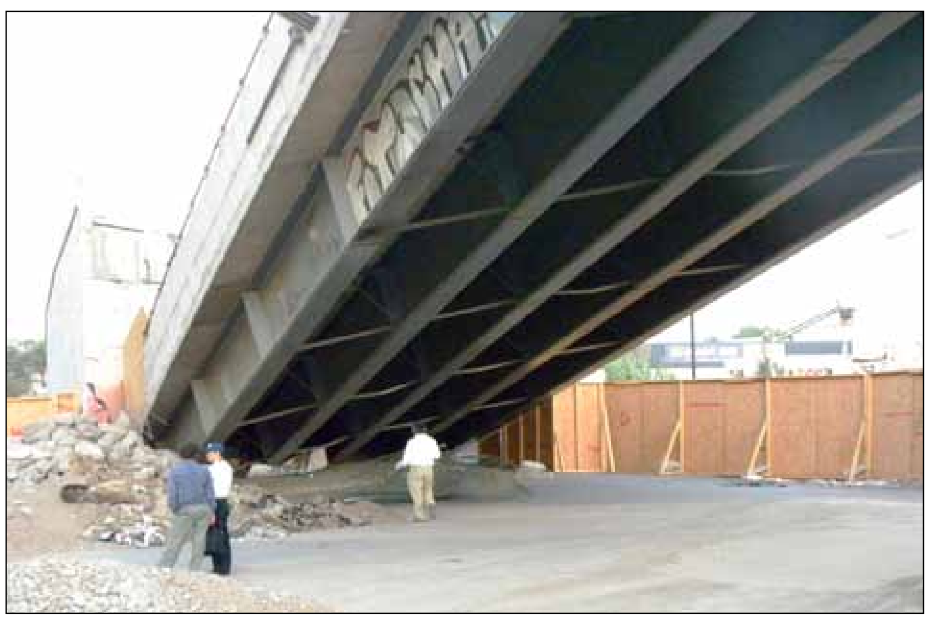

Figure 25. *Unseating at the abutment of the skewed steel plate girder, Matta-Quilicura Bridge, north of Santiago, due to insufficient support length (photo: J. Arias).*

Figure 26. *Shear failure in a column in northern approach to Juan Pablo II Bridge across Bio-Bio River, Concepción, due to lateral spreading and the propping action of the superstructure at the top of the column (photo: J. Arias).*

large ENAP refinery or the CAP steel mill in the San Vicente/Talcahuano area. Both facilities were out of production and appeared to have suffered significant structural damage.

Food Processing Facilities and Warehouses. The team entered only a limited number of these structures, but it appeared that most light industrial steel buildings performed well, even if the anchorages at the column bases would have been considered insufficient by today's standards. Similar precast concrete structures did not fare so well, as there was evidence of connection distress in the wall panel connections and some panel collapses. Numerous examples of silo failures were observed; performance depended on support details and whether silos were full. Storage racks seem to have performed well even if the anchorage to the floors was minimal; however, most of their contents fell to the floor in the extended shaking. A number of spectacular collapses of stacked, unsecured storage drums and similar items were evident in food processing facilities.

Social Impacts, Response, and Recovery

In the 1960 Valdivia earthquake, 428 Chileans per million lost their lives; by comparison, only 31 Chileans per million lost their lives in the 2010 quake. This can be attributed to effective governance as measured by economic prosperity, physical infrastructure standards, construction code enforcement, and state-society institutional assets. Table 3 presents a damage assessment overview. Chile offers important lessons in disaster policy and highlights the interplay between pre- and post-disaster social and spatial inequalities. There is an excellent opportunity for long-term policy-relevant research on the rebuilding of families, housing, neighborhoods, communities, livelihoods, and economies.

Governance and Territorial Order. There are four tiers of territorial planning: national, regional (involving one or more provinces), intermunicipal, and municipal. Nationally, the Ministry of Housing and Urban Development is in charge of regulations and ordinances for urban development and land use, building construction, and community facilities. The Ministry of the Interior is in charge of regional plans (**http://www.subdere.gov.cl**). Regional planning is legally delegated to administrative regions by way of territorial regulatory plans and intermunicipal plans, while municipal plans and district plans fall under the authority of municipal governments. Neighborhood organizations provide local linkages to municipal and district planning. The Ministry of Planning (**www.Mideplan.cl**) works on the social well-being aspects of development.

Risk reduction and emergency measures are articulated, if inconsistently so, at the various tiers of territorial planning. Since 2002, the Program of Updating Territorial Planning Regulations has modernized Chile's instruments of urban and regional planning, though it does not yet mandate risk assessment at each level of regional and local planning. Natural hazard risks are to be ad-

Figure 27. *Base-isolated wharf at Coronel (photo: E. Miranda).*

Figure 28. *Typical damage to storage tanks in wineries (photo: R. Leon).*

dressed in detail in a city-level general plan, but disaster management often suffers from tensions between territorial planning guidelines and private land development interests, especially in coastal zones. A National Coastal Commission contributes to the formulation of coastal land use policy; however, its recommendations are not binding. The Ministry of the Interior's SUBDERE (*Subsecretaria para Desarrollo Regional y Administrativo*) serves as an intermediary between central government and regional-local government.

Disaster Response. In general, the Chilean government did not demonstrate sufficient central, regional, and local capacity for quick response to disaster events. The central government's National Emergency Management Office (ONEMI), located in the Interior Ministry, is small.

In the early weeks, regional ONEMI offices were understaffed and lacked direction from the main office in Santiago. The Army has been widely praised for its effectiveness and comportment in maintaining post-disaster order, but it was not deployed immediately for various reasons, some having to do with its historical association with General Pinochet.

Although municipal emergency committees carried out search and rescue and damage assessment professionally, given the resources available, the central government's slow emergency response led to some looting and breakdown in civic order. The plight of the poor living in overcrowded conditions was brought to public awareness and everyone could see the two faces of the country: the modern versus the marginalized.

The new president, Sabastian Piñera, is beginning the task of improving the coordination of emergency management and alert between ONEMI and ministries such as Defense, Interior, Housing and Urban Development, Health, and Education, Public Works, and the Hydrolographic and Oceanographic Institute. Clearly, the communication system requires upgrading, as the disaster interrupted cell phone service, and few satellite phones are available.

The need to strengthen local capacities refers not just to governments, but also to synergies with non-governmental organizations. Universities responded quickly to the disaster by supplying volunteers and other levels of support. The Red Cross (with centers in Santiago, Talca, and Concepción) and the Catholic Church, operating through CARITAS, have been leaders in providing medical, material, social, and psychological assistance. The Catholic Church's housing NGO, "Un Techo para Chile," has built small housing settlements (30-40 units on a site) in many affected cities.

Insurance. Insured losses from the earthquake are estimated in the $US 6-9 billion range. By law, the water and electricity utility companies (which are privatized) are re-

Table 3: Estimated Losses by Category

Loss Category	Amount	Location
Deaths	521	All regions
Missing	56	All regions
Victims (estimated injured, lost housing, died, and missing)	800,000	All regions
Housing (damaged or destroyed)	200,000	All regions
Housing (damaged or destroyed)	12,000	Santiago
Economic losses	US $30 billion	All regions
Employment loss	15,000 jobs lost	All regions
Public sector losses	US $9.33 billion	All regions
Houses (total loss)	81,440	All regions
Houses (heavy damage)	108,914	All regions
Houses (minor damage)	179,683	All regions
Housing damage	58,000	Maule region
Catholic churches (heavily damaged)	444	47% of all churches in the country
Impacted small cities	45	Over 5,000 inhabitants
Impacted large cities	5	Over 100,000 inhabitants
Secondary schools (some damage)	4,013	All regions

Source: Chile government documents

Figure 29. *Families displaced to temporary tent camps in the center of Talca. Construction of simple wood frame shelter is under way (photo: G. Franco).*

quired to have disaster insurance. Churches and public buildings were not insured, while insurance coverage for residential buildings varied. Ninety-five percent of households with mortgages did carry the required seismic insurance, but few who owned their houses without a mortgage did. Although content coverage is very low, owners are paid full structural coverage if a house cannot be repaired, and six months of rent if it is not habitable. There was no insurance for adobe buildings, which represented two-thirds of the residential losses.

Reconstruction. Many families have camped out across from their destroyed or damaged houses in small settlements of 10-12 families, and most expect to return to and rebuild on their own parcels. Other victims are living with family or friends in nearby towns, or are renting locally if possible. Structures have been quickly demolished in many towns and cities. Most buildings that had been declared unsafe were bulldozed within two weeks of the event in order to prevent people from returning to them.

The central government proposes a variety of recovery housing solutions. For families living in government-supported apartments, their units will be rebuilt on site. Extremely poor families, and families who lost their houses, have no titles, or live in high-risk zones will be relocated to new locations, and such settlements will be supported by the Housing Solidarity Fund. Destroyed or severely damaged adobe houses in rural and urban zones will be rebuilt on the same sites with support from the Housing Solidarity Fund and the Construction in Residential Sites Program.

Damaged houses in zones of traditional (*típica*) Chilean building style will be rebuilt to original styles with special architectural heritage funds. People lacking earthquake insurance, but not poor, will be able to obtain a favorable bank loan. Low-income families will be provided a subsidy and technical assistance for repair of their dwellings.

Closing Remarks

Chile is a country with stable institutions and a prosperous economy that, in response to a history of frequent strong earthquakes, has developed and implemented programs and standards to improve safety and selective infrastructure operability following major earthquakes. Like many other economically developed countries in the world, including the United States, however, Chile is also a nation of income inequality and many marginal structures that are at higher risk to earthquake effects. The February 27, 2010, earthquake, with its long durations of earthquake ground shaking and ensuing tsunami inundation, demonstrated both the effectiveness and the shortcomings of modern earthquake risk reduction programs. Consequently, the earthquake and its effects are especially relevant and important to seismic risk reduction activities in other earthquake-prone parts of the world.

This brief report highlights some of the principal observations from a number of reconnaissance teams that studied the February 2010 earthquake. The earthquake and its effects put forth a wealth of data, some already gathered and some yet to be discovered, on subjects including seismology; geologic and geotechnical effects; strong earthquake ground motion; tsunami; performance of buildings, bridges, and lifelines; early warning, emergency response, civil protection, and health care; and social impacts and long-term recovery. Continued study, including focused research and detailed documentation, can produce data and procedures to more effectively reduce losses and improve resilience following future earthquakes. Team members urge that these studies become a high priority.

Figure 30. *The Puertas Verdes Camp in the outskirts of Constitución has capacity for about 100 families (photo: G. Franco).*

Team Members

The EERI team. Co-Team Leaders: Jack Moehle (UC Berkeley), Rafael Riddell (U Católica), and Rubén Boroschek (U Chile).

Team Members: Tony Allen (WA DOT), Daniel Alzamora (FHWA), Juan Arias (U Nevada-Reno), Scott Ashford (Oregon State U), Richard Bissell (U Maryland), Ian Buckle (U Nevada-Reno), Mehmet Çelebi (USGS), Alvaro Celestino (Degenkolb Engineers), Genda Chen (MO Univ Science & Technology), Gary Chock (Martin and Chock, Inc.), Jeff Dragovich (NIST), Luis Fargier Gabaldon (U Los Andes, Venezuela), Guillermo Franco (AIR Worldwide), Jeffrey Ger (FHWA), William Holmes (Rutherford & Chekene), Tom Kirsch (Johns Hopkins U), Roberto Leon (Georgia Tech), Joe Maffei (Rutherford & Chekene), Mike Mahoney (FEMA), Eduardo Miranda (Stanford), Judith Mitrani-Reiser (Johns Hopkins U), Gilberto Mosqueda (SUNY Buffalo), Gokhan Pekcan (U Nevada-Reno), Rodrigo Retamales Saavedra (Rubén Boroschek y Asociados Ltda.); Ian Robertson (Hawaii-Manoa), Carlos Sempere (Forell/Elsesser), Mark Sereci (Digitexx Data Systems), William Siembieda (Cal Poly, San Luis Obispo), Jennifer Tanner (U Wyoming), Richard Tardanico (Florida International U), John Wallace (UCLA), Mark Yashinsky (Caltrans), W. Phillip Yen (FHWA), Farzin Zareian (UC Irvine).

The following additional individuals from three Chile universities contributed generously to the EERI team reconnaissance.

Federico Santa Maria Technical University: Professors Patricio Bonelli and Carlos Aguirre, with Arturo Millán.

The Pontificia Universidad Católica de Chile: Professors Juan Carlos De La Llera, Matias Hube, and Carl Lüders, with Vicente Ariztía, Juan Jose Besa, Alvaro Carboni, Claudio Frings, Juan Pablo Herranz, Cristobal Moena, Rodrigo Oviedo, Victor Sandoval, Nicolas Santa Cruz, César Sepúlveda, and Benjamin Westenenk.

The Universidad de Chile: Professors María Ofelia Moroni, Leonardo Massone, and Rodolfo Saragoni.

Individuals from the Ministerio de Obras Públicas who greatly assisted the bridge team include José Ortega, Mauricio Guzmán and Sandra Achurra.

The GEER team. Co-Team Leaders: Jonathan Bray (UC Berkeley), David Frost (Georgia Tech), Ramon Verdugo (U Chile), Christian Ledezma (U Católica), and Terry Eldridge (Golder Associates).

Team Members: Pedro Arduino (U Washington), Dominic Assimaki (Georgia Tech), Youssef Hashash (U Illinois),Tara Hutchinson (UC San Diego), Laurie Johnson (Laurie Johnson Consulting), Keith Kelson (Fugro William Lettis & Associates), Robert Kayen (USGS), Gonzalo Montalva (U Concepción), Robb Moss (Cal Poly SLO), George Mylonakis (U Patras), Scott Olson (U Illinois Urbana-Champaign), Kyle Rollins (BYU), Nicholas Sitar (UC Berkeley), Jonathan Stewart (UCLA), Alfredo Urzúa (Prototype Engineering Inc.), Rob Witter (Oregon Dept of Geology and Mineral Industries), and Nick Zoa (U Maryland).

Contributors: Scott Ashford (Oregon State U), David Baska (Terracon), Jim Bay (Utah State U), Rodrigo Betanzo (U Concepcion), Rubén Boroschek (U Chile), Gabriel Candia (UC Berkeley), Leonardo Dorador (U Chile), Aldo Faúndez (Servicio de Salud Arauco), Gabriel Ferrer (U Católica), Lenart González (Golder Assoc.), Katherine Jones (UC Berkeley), Dong Youp Kwak (UCLA), Jaimé Salazar Lagos (Burgos Arquitectos), José Miguel Lopez (Vale Exploraciones), Walter Lopez (UCLA), Eduardo Miranda (Stanford), Claudio Medina (Golder Assoc.), Sebastian Maureira (U Chile), William Siembieda (Cal Poly, San Luis Obispo), Constanza Tapia (U Católica), Mesut Turel (Georgia Tech), and Claudia Welkner (Golder Associates).

A Humboldt State University team, operated through UNESCO's International Tsunami Survey Team protocols, included Team Leader Lori Dengler (HSU), Troy Nicolini (NWS), Sebastian Araya (Stillwater), Nick Graehl (HSU grad student), and Francisco Luna (freelance journalist).

The TCLEE team. Team Leader Alex Tang, (L&T Consulting Inc); Team Members: Sonia Castellanos of Emerson Network Power; Tom Cooper (T. W. Cooper Inc); Leonardo Dueñas-Osorio (Rice U.); John Eidinger (G&E Engineering System); Bill Fullerton (The Louis Berger Group Inc); Eduardo del Canto Hidalgo (Civil Aeronautics Administration); Roy Imbsen (Earthquake Protection Systems, Inc); Leon Kempner (Bonneville Power Adm); Alejandro Kolbe (Ministry of Public Works); Alexis Kwasinski (UT Austin); Solange Loyer (Universidad Católica de la Santísima Concepción); Juan Arrese Luco (Ministry of Public Works); Eduardo Mesina (Ministry of Public Works); Rodrigo Lopez Muela Parra (Civil Aeronautics Administration); Allison Pyrch (Shannon & Wilson Inc); Hugh Rudnick (Catholic University, Santiago); Anshel Schiff (Stanford); Mauricio Villagran (Universidad Católica de la Santísima Concepción); Yumei Wang (Oregon Dept Geology and Mineral Industries).

Acknowledgments

The research, publication, and distribution of this report were funded by the EERI Learning from Earthquakes project, under grant #CMMI-0758529 from the National Science Foundation (NSF). Geology and geotechnical engineering aspects were based on GEER studies supported by NSF under Grant # CMMI-1034831.

Any opinions, findings, and conclusions or recommendations are those of the authors and do not necessarily reflect the views of NSF. FHWA and PEER provided financial support for the bridge reconnaissance team. ASCE provided financial support for the TCLEE report on lifelines.

The success of the reconnaissance teams was a direct result of generous assistance of numerous individuals and organizations in Chile. The list of names is too long to include in this short report but instead can be found at http://www.eqclearinghouse.org/20100227-chile/published-reports/eeri-newsletter-insert/additional-acknowledgments.

References

Astroza, M., F. Cabezas, M. Moroni, L. Massone, S. Ruiz, E. Parra, F. Cordero, A. Mottadelli, 2010. *Intensidades Sismicas en el Area de Daños del Terremoto del 27 de Febrero de 2010.* Santiago: Univ. of Chile.

Boroschek, R., P. Soto, L. Leon, D. Comte, 2010. *Central-South Chile Earthquake February 27, 2010. 4th Preliminary Report.* Univ. of Chile, April 5 (Spanish).

Cisternas, M, B.F. Atwater, F. Torrejo´n, Y. Sawai, G. Machuca, M. Lagos, A. Eipert, C. Youlton, I. Salgado, T. Kamataki, M. Shishikura, C. P. Rajendran, J. K. Malik, Y. Rizal & M, Husni, 2005. “Predecessors of the giant 1960 Chile earthquake,” *Nature*, V. 437, doi:10.1038, p. 404 – 407.

El Mercurio, 2010. “Gobierno evalúa norma de edificación costera,” March 31, http://diario.elmercurio.cl/detalle/index.asp?id={6b20c703-8069-41a5-bb6a-28b9ac30dae6}.

Forensic Medical Service (SML), 2010. Lista fallecidos, http://www.interior.gov.cl/filesapp/Lista_fallecidos.pdf.

GEER, 2010. “Geo-engineering Reconnaissance of the 2010 Maule, Chile Earthquake,” report of NSF-Sponsored GEER Association Team, J. Bray & D. Frost, eds., http://www.geerassociation.org/

International Tsunami Information Center (ITIC), 2010. 27 February 2010, MW 8.8, Off Central Chile, http://193.191.134.38/itic/index.php?option=com_content&view=article&id=2&Itemid=5.

Los Angeles Times, 2010. “In Chile, a father’s hope washed away,” March 22, http://articles.latimes.com/2010/mar/21/world/la-fg-chile-survivor22-2010mar22.

Ministry of the Interior, Chile, 2010. www.interior.gov.cl.

Ministry of Housing, Chile, 2010. http://www.minvu.cl/opensite_det_20100329164111.aspx.

National Geophysical Data Center (NGDC), 2010. NOAA/WDC Historical Tsunami Data Base, http://www.ngdc.noaa.gov/hazard/tsu_db.shtml.

National Seismological Service, 2010. *Cauquenes Earthquake, February 27, 2010*. Servicio Sismologico Technical Report, Univ. of Chile, April 3 (Spanish).

Ruegg, J.C., et al., 2010. “Interseismic strain accumulation measured by GPS in the seismic gap between Constitución and Concepción in Chile,” *Physics of the Earth and Planetary Interiors*, 175, pp. 78-85.

Technical Council on Lifeline Earthquake Engineering (TCLEE), 2010. “Preliminary Report on the 27 February 2010 Mw8.8 Offshore Maule, Chile Earthquake.” http://www.eqclearinghouse.org/20100227-chile/published-reports

The Independent, 2010. How 12-year-old girl saved her Chilean island from catastrophe, March 4, http://www.independent.co.uk/news/world/americas/how-12yearold-girl-saved-her-chilean-island-from-catastrophe-1915821.html.

United States Geological Survey (USGS), 2010. http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/#details.