Technical Council on Lifeline Earthquake Engineering (TCLEE)
Preliminary Report
27 February 2010 M_w8.8 Offshore Maule, Chile Earthquake

Introduction

The TCLEE Maule Chile earthquake team conducted a post earthquake investigation of the lifelines performance in the impacted region from 10 – 17 April. This report provides a summary of:

- Electric Power
- Telecommunication
- Water and Wastewater
- Gas and Liquid Fuel
- Ports
- Airports
- Roads and Bridges
- Railroads
- Lifeline Interdependence and Resilience

as well as information on the earthquake setting and geotechnical aspects. Significant mitigation efforts against earthquake losses have been going on in Chile since the two large earthquakes that occurred in 1960 and 1985. The low number of casualties that occurred in this large earthquake is an obvious result of these mitigation efforts. With respect to lifelines, many more lessons will be learned from this latest earthquake, particularly in the area of interdependence. The study of lifeline resiliency must continue with a focus on cost effective expenditures for earthquake preparedness to lifeline service providers.

TCLEE Team

The post Maule, Chile Earthquake lifeline performance investigation obtained excellent local support from the local and national governmental organizations, universities and utilities. As a result of this professional collaboration, the TCLEE team exceeded our expectation for collection of performance data and perishable information. Team members are currently preparing a TCLEE monograph using the information gathered during our field visit. All figures in this preliminary report were captured by the team members unless credited in the caption. All members of the TCLEE team contributed to this report.

The TCLEE team consists of:

- Alex Tang, Team Lead (telecommunication, power, airport, port)
- Tom Cooper (gas and liquid fuel, tanks, refinery, pipeline)
- Leonardo Dueñas-Osorio (lifeline interdependence, resilience)
- John Eidinger (water and waste water, electric power)
- Bill Fullerton (airport, social impact – relief)
- Roy Imbsen (highway, bridge, overpass)
- Leon Kempner (electric power transmission)
- Alexis Kwasinski (electric power, telecommunication, interdependence)

- Allison Pyrch (geotechnical, geology, tsunami)
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Summary

Significant mitigation efforts against earthquake losses have been going on in Chile since the two large earthquakes that occurred in 1960 and 1985. The low number of casualties that occurred in this large earthquake is an obvious result of these mitigation efforts. With respect to lifelines, many more lessons will be learned from this latest earthquake, particularly in the area of interdependence. The study of lifeline resiliency must continue with a focus on cost effective expenditures for earthquake preparedness to lifeline service providers.

Geologic Aspects

The geological aspects include information on the earthquake characteristics, plate tectonic setting, historic seismicity, seismological characteristics of the earthquake, the tsunami, recorded ground motions, local geologic conditions. Out of the reported 486 casualties, more than 200 were due to the tsunami that arrived within as little as 10 minutes after the strong shaking.

On February 27, 2010, at 3:34 A.M. local time, there was a moment magnitude (Mw) 8.8 earthquake off the west coast of Maule region, Chile. This earthquake, which was located offshore at 35.909°S, 72.733°W with a depth of 35 km and had a plate rupture of about 550 km by 150 km, shook a large region with an estimated 80% of Chile's population. The epicenter is located 335 km SW of the capitol city of Santiago and 105 km NNE of the coastal city of Concepcion. Numerous large aftershocks occurred over the months, including over 130 magnitude 6 or higher aftershocks within the following week.

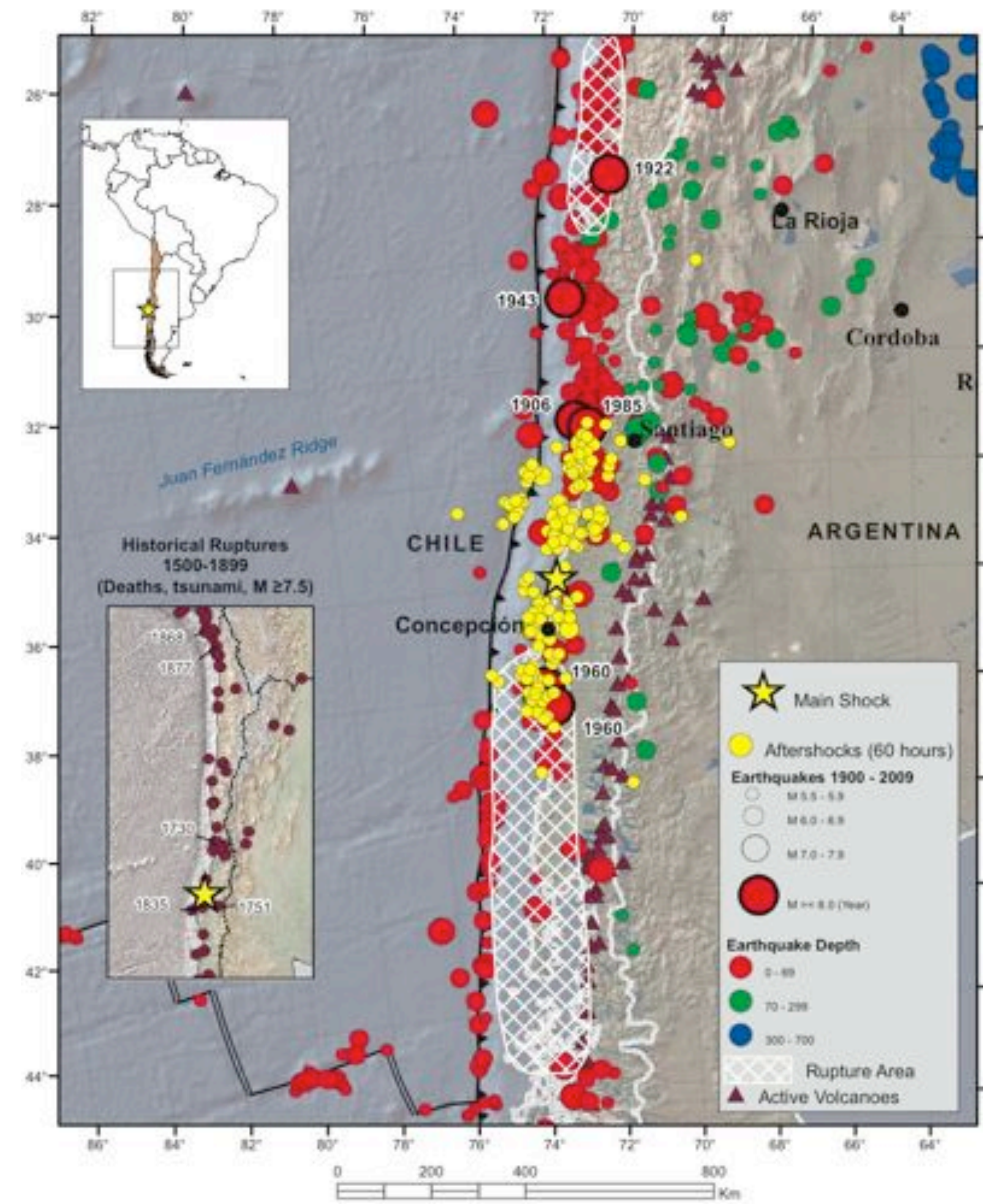
The Maule Chile earthquake, which occurred at a converging plate boundary, was a subduction zone earthquake. The earthquake occurred in a region of known high seismicity at the interface between the Nazca plate and the South American tectonic plates. The Nazca plate is converging eastward at a rate of about 80 cm per year. Chile has a long history of large earthquakes, including great subduction zone earthquakes of magnitude 8 or larger (see Table 1: Great Historic Earthquakes in Chile).

Table 1. Great Historic Earthquakes in Chile

1575 Valdivia earthquake	8.5
1730 Valparaiso earthquake	8.7
1751 Concepción earthquake	8.5
1835 Concepción earthquake	8.5
1868 Arica earthquake	9.0
1906 Valparaíso earthquake	8.2
1922 Vallenar earthquake	8.5
1943 Coquimbo earthquake	8.2
1960 Valdivia earthquake	9.5
1985 Santiago earthquake	8.0
1995 Antofagasta earthquake	8.0

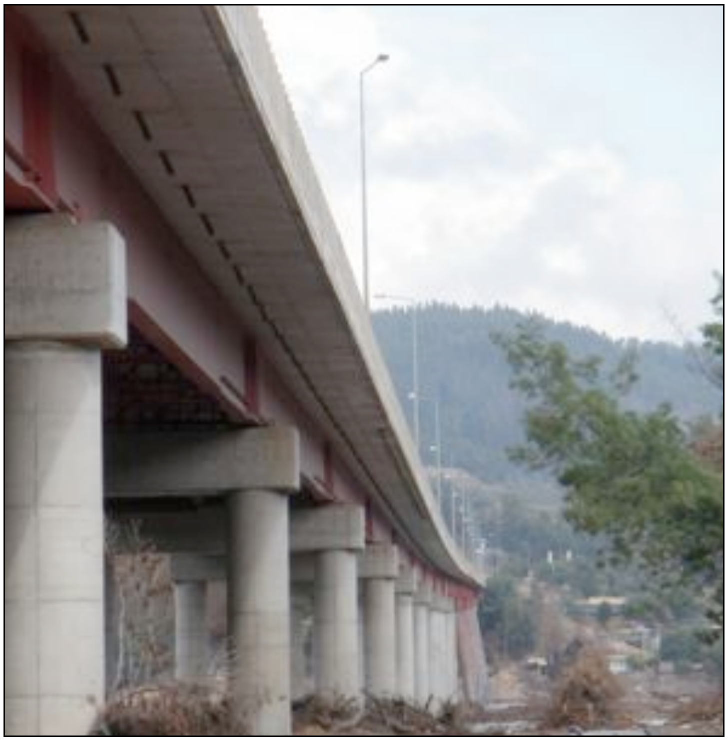
In addition to the main shock, which caused coastal regions to both uplift and subside, tsunami waves hit the low lying Chilean coastline as well as distant shores across the Pacific Ocean. The tsunami, which fortunately occurred during a low tide, had various characteristics up and down the coast. Along the south coast, there were three main surges, which resulted in a maximum run-up height of 20 m and a maximum inland inundation distance of 12 km from the coastline. Out of the reported 486 casualties, more than 200 were due to the tsunami that arrived within as little as 10 minutes after the strong shaking.

The earthquake resulted in maximum recorded peak ground accelerations in the Concepcion area of 0.65g with over 60 seconds of strong shaking. The Modified Mercalli Intensity of VIII was experienced in a number of coastal and inland communities. Due to the large epicentral region, the geologic conditions vary from mountainous terrain and valleys to river and coastal terrains. The ground water conditions were favorably low because the earthquake occurred towards the end of summer. As a result, fewer landslides and ground related failures related to liquefaction, lateral spreading and bearing capacity occurred. Certain areas were subjected to focusing of high seismic energy as well as ground motion amplification due to soft soils.



Chile Earthquakes from 1900 - 2010 (USGS)

Earthquake location map, including main shock, aftershocks, and historic earthquakes. Source: http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/20100227_Main.pdf



Tsunami damage to bridge in Constitucion. The bridge girder was lifted by the tsunami and moved inland about 1 ft for a distance of about 6 bents. During the TCLEE team visit on April 16, 2010, the bridge traffic was being controlled to one lane of traffic. Team members witnessed official search activities for missing persons.

Dichato Tsunami damage

Geotechnical Aspects

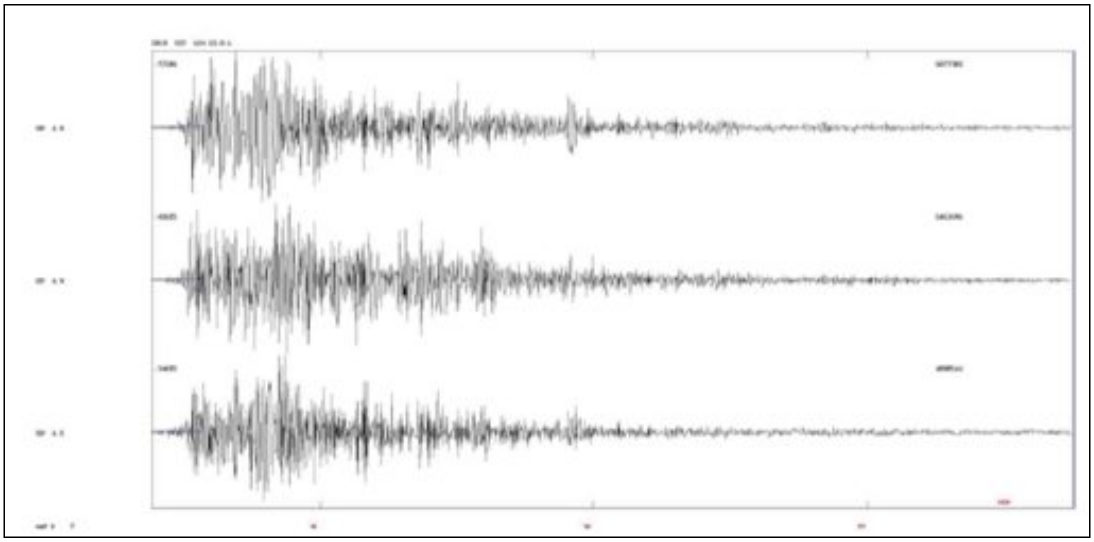
The level of ground shaking was controlled by the rupture pattern, the proximity to the earthquake rupture and the local soil conditions. Ground shaking and geotechnical related ground failures impacted all lifelines and resulted in damage to buildings, bridges, highways, railways, ports, and systems involving water, waste water, gas and liquid fuel, electrical, telecommunication, as well as contributing to lifeline interdependency issues. Geotechnical related failures involve soft soil site amplification, bearing capacity and fill failures, slope and dam failures, and liquefaction and lateral spreading failures especially near waterways. Areas with engineered soils including industrial facilities on wetland sites, retaining walls and ground improvement appeared to perform well. Refer to the lifeline chapters for more details.

The areas nearest the rupture plane generally experienced a moderate level of ground deformation ranging from extensive-to-none in areas by the rivers, coast, floodplains, lowlands, and dunes. The most extensive lifeline damage was observed closest to the coast, with a concentration in areas of poor soils that failed through liquefaction, lateral spreading, settlement, or was inundated by the tsunami. The areas that experienced liquefaction and lateral spreading are concentrated in the lowlands with high ground water conditions. Liquefaction occurs during earthquake shaking. Loose, saturated sandy soils can contract, which can lead to an increase of pore water pressure. When pore water pressure increases, the effective stress reduces, and soils can “liquefy.” Liquefaction is often associated with lateral spreading and permanent ground displacements in the down gradient direction. Several coastal and river vicinities experienced extensive liquefaction, resulting in sand boils and fissures, and lateral spreading.

In the city of Concepcion, ground motions recorded on bedrock appear rich in low frequency energy and had uncorrected maximum recorded peak ground accelerations of 0.65g in the north-south direction, 0.58 g in the east-west direction, and 0.60 g in the vertical direction (see figure). Ground motions on alluvial sites are expected to substantially lower; however, no recordings have been obtained. As an example, Concepcion’s waste water plant was developed on an extensive site adjacent to the Bio Bio River mouth near the Pacific Ocean. This site experienced extensive liquefaction, including sand boils, fissures, settlement, and lateral spreading, which led to extensive damage and will require many more months to repair. Another example is south of Concepcion in coastal Coronel, the fishing port experienced liquefaction and lateral spreading (see figure).

Several lifelines incorporate compacted engineered fill into the construction of their infrastructure, including wetland sites in the vicinity of Concepcion, earthen dams, levees, bridge abutments, road embankments, and cut-and-fill roads. For the most part, engineered fill soils performed well. In Concepcion, geotechnical ground improvement was conducted in two limited areas at the ENAP oil refinery. Stone columns and micropiles supporting heavy equipment were reported to perform well with no observed ground settlement in the vicinity.

This earthquake only caused minimal slope failures in a few localized areas. Areas that experienced earthquake-triggered landslides were mostly in areas of weak slopes and previous landslide terrain. Road cuts and steep slopes that were marginally stable before the earthquake were commonly destabilized from the ground shaking. Reactivation of meta-stable landslides, such as in the coastal town of Iloca, and activation of slopes that have been undercut by river or wave erosion or road building activities was observed.



Accelerogram from San Pedro High School station in Concepcion. Source: University of Chile, Santiago. (Report titled: Informe Tecnico, Teremoto Cauquenes 27 Febrero 2010, Servicio Sismologico, 3 Abril 2010.)

Liquefaction and lateral spreading damage at Coronel fishing port. Note the damaged lifeline.

Electric Power

The transmission network performed reasonably well and was ready to provide power within 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 live-tank circuit breakers, which are used sparingly in the western United States. We understand that more than

25 failures occurred within these elements, but that these failures represented a small percentage of their inventory. Over the last 25 years, the backbone 220 kV and 500 kV systems were designed with earthquake provisions considered. This system was located mostly in areas with modest levels of ground motions (PGA = 0.10g to 0.25g) and performed reasonably well overall. Lower voltage sub-transmission systems near the coast, which experienced higher levels of ground shaking (PGA = 0.2g to 0.45g), also suffered sporadic damage. While there were a few exceptions, seismic practices, such as equipment anchorage and slack in conductor connecting equipment, were done very well.

The low voltage (34.5 KV and below) distribution system sustained minor damage due to collapsed buildings and damaged poles. The hardest hit regions were Region VII and Region VIII. We understand that one company had to replace a total of 450 poles and lost 1,500 poles out of an installed base of 759,000, and 82 transformers out of 50,109. Most of these losses were in the tsunami areas. The underground distribution cable network worked well. Resources from other companies and neighboring countries came to help the restoration effort. Two weeks after the earthquake, the distribution system service was restored.

Pantograph disconnect switch

Damaged candlestick style live-tank circuit breakers

Telecommunication

All service providers, both landline and wireless services, experienced extensive setbacks due to 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—Central Offices over 5000 subscribers, MTSOs (Mobile Telephone Switching Offices), and fiber backbone carrier offices—have backup power generators. Majority of the cell sites and remote offices have 3 to 4 hours and 8 hours of battery reserve power, respectively. The earthquake occurred at 3:34 AM in the morning, by about 6:30 AM most cell sites and remotes sites ran out of power. Due to damage to roads and bridges, access to these sites became extremely difficult to set up generator to power the transmission equipment. We observed that most network operators have an insufficient number of portable generators to power all the sites. About 50% of the cell sites had battery failures because of damage to batteries. Failures during shaking were due to the fact that most of the battery racks were not anchored and batteries were not secured on the shelves of the battery racks. Fallen antenna from towers were another common occurrence in Regions VII and VIII. A number of cell sites installed on roofs of commercial buildings were damage when the buildings were structurally damaged. Cell site towers are designed based on wind load. Based on our collected information, one operator had issues with antennas in 50 % of their sites. At least two towers collapsed, one was a monopole design on poor soil while the other was mounted on a concrete water tank that collapsed.

Both landline and wireless services were restored 7 days after the earthquake. Many utilities that relied on wireless service were having difficulties within the first week after the earthquake to dispatch maintenance crews to damaged sites in order to restore service.

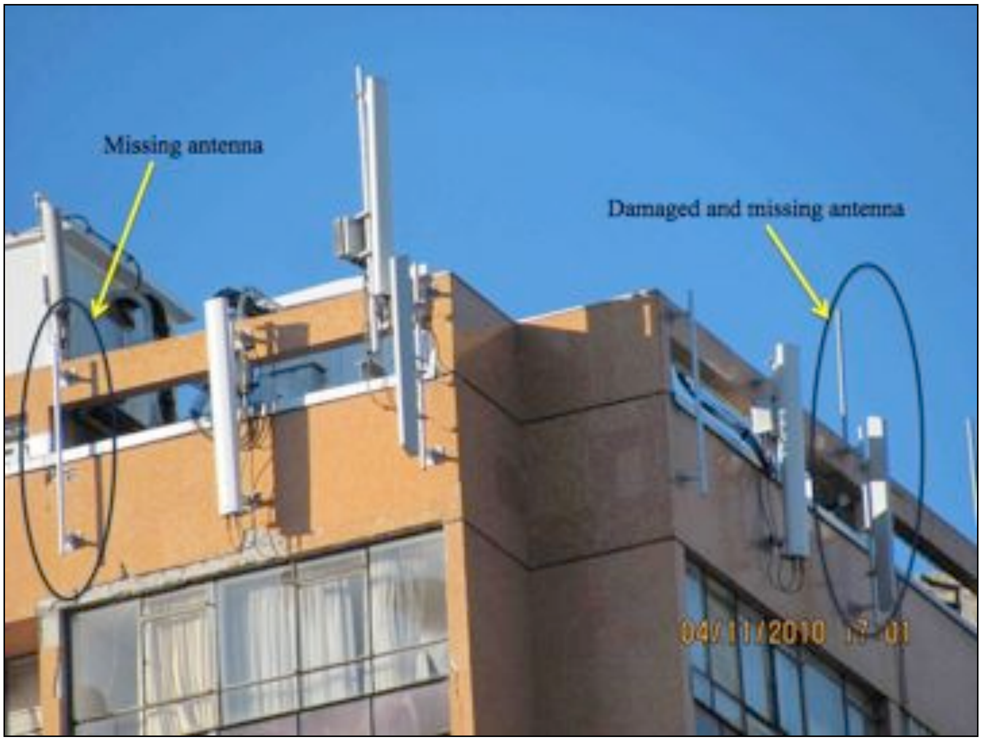
Another example of damage is that a backup generator failed due to a transfer switch problem, which was used to power the air conditioner. This caused overheating of electronic components that resulted in equipment malfunction.

About 70 % to 80 % of the cell sites in regions VII and VIII had problems with either equipment or antenna damage. This rate falls to about 50 % in region V, mostly in sites located in rooftops. Cell sites do not typically anchor equipment. Switches and MTSOs have seismic designed equipment. Fallen perimeter walls or nearby construction collapse affected operation in a few cell sites.

Although fiber optic cables were severed in many locations mostly due to collocating on bridges and overpasses, alternative links provided by another company allowed to some transmission circuits for inter LATA (local access and transport area) operation.

Close to 200 outside plant DLC or DSLAM remote terminals were affected mostly due to lack of power. Close to 150,000 landline subscribers were affected mostly in small remote offices with less than 5000 subscribers again due to power problem as none of these sites have backup power generators.

There were many logistical problems in order to refuel sites with permanent generators or at sites where portable generators were deployed. It was difficult to buy or rent portable generators. Some of them were provided by affiliated companies outside of Chile. Diesel supply was difficult to ensure. Some network operators had some supply contracts in place before the earthquake. Road conditions and lack of power at diesel supply points affected recovery operations. Lack of personnel and need for maintenance also affected diesel supply. Theft of batteries, generators and diesel was an additional problem not expected.



Fallen cell site antenna

Unsecured batteries on unanchored battery rack fell off the rack and damaged (Courtesy Carlos Urzua Acuña)

Water and Wastewater

Essbio Potable Water

Essbio serves potable water in urban communities, totaling about 4,000,000 people served. Each community's system is separate, and not interconnected. In total, the potable water systems include about 7,000 km of transmission and distribution pipe, of which 1,200 km in the city of Concepcion.

By far the largest amount of damage to the various Essbio water systems was concentrated in Concepcion and Talcahauno. Common ground motions on firm ground in Concepcion were about PGA = 0.3g (+/- 50% locally); areas within 200 feet (or so) of river banks often suffered lateral spreads and settlements. Tsunami inundation did not impact most of the Concepcion-area water system; where tsunamis did impinge on port areas, coincident destruction to buildings and failure of sea walls led to damage to buried water pipes. Damage to the Concepcion-area water treatment plant included: severe damage to the raw water intake structure, due to a combination of lateral spreads and ground shaking; internals damage to the four clarifiers (baffles, settlers and supporting elements); damage to suspended ceilings (control room, water quality laboratory); toppling of control room computer monitors and computers); toppling of water quality equipment and glassware from countertops. In the Concepcion-area distribution system, there were 72 breaks or leaks to large diameter (500+ mm diameter) 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. Prior to the earthquake, the net leak rate (lost water) in the system was about 40%. As of April 12, 2010, it was about 60%.

Rural Potable Water Systems

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 strong earthquake-shaking areas. At least 73 of the elevated tanks completely collapsed. Tank failures were due to inertial overloads.

Santiago Potable Water System

The Santiago water system includes two large water treatment plants on the east side of the city (PGA perhaps 0.10g). Ground shaking in the greater Santiago metropolitan region was commonly PGA = 0.15g to 0.20g, with local variations ±50%. Potable water outages in the Santiago area were sporadic in geographic area; many areas had no outages.

Wastewater Systems

Wastewater systems suffered heavily, including damage to waste water 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.

Canals

Water canals and hydraulic structures (levees, river embankment defenses) are used in many areas in Chile to deliver water from the Andes to communities in the central agricultural areas for irrigation purposes. As of April 1, 2010, the status of these facilities was as follows: $ 2,111,000 for emergency repairs; $57,700,000 projected for long term repairs. 42 facilities were initially categorized initially as being in an extreme emergency condition; 32 in serious condition; 25 collapsed; 38 had various levels of structural damage; 1 overflowed; 2 ruptured.

Other Factors

Within 8 hours after the earthquake, there was general chaos in the Concepcion area. This included looting of stores, and setting fires. The local police could not maintain safety. It took three days for the military to show up in Concepcion, after which crowd control was restored, often at gunpoint.

Two fires were reported in the Concepcion area after the earthquake. Both fires were reported to have been set by people. Almost none of the general building stock uses wood materials. No earthquake-ignitions or fire spread occurred.

Collapsed wall at Concepcion Water Treatment Plant Raw Water Pump Station

Damaged Large Diameter Welded Steel Water Pipe (Courtesy WWPP Chile)

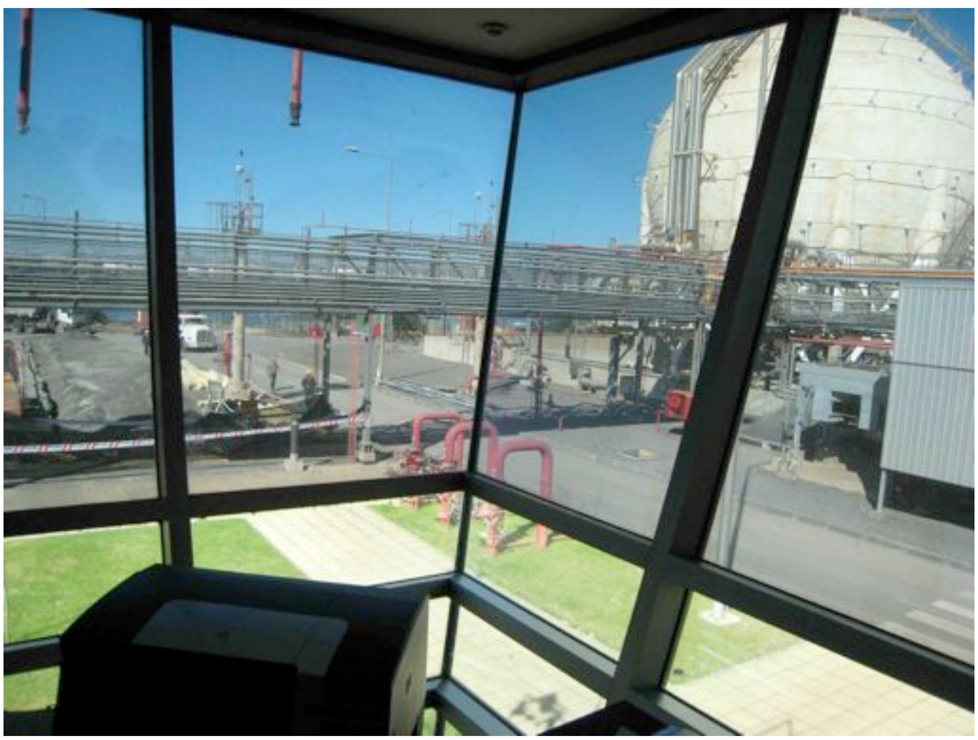
Typical Collapsed Elevated Small Steel Tank (Constructed 1999)

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, check critical elements, appraise possible damage) with only minor, non-critical damage. The Aconcagua refinery near Santiago had minor damage and restarted 10 days after the earthquake. The capacity of this refinery is about 98,000 bpd. The Bio Bio refinery near Concepción sustained what could be considered minor damage, except that the refractory in the heaters fell to the heater floors, precluding the use of the heaters. The Bio Bio refinery was shut down after the earthquake. One of the two steel crude oil pipelines that feeds 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. Tank sloshing occurred in floating roof tanks with resulting spillover of product. One floating roof tank developed a leak due to local ground failures.

Santiago is supplied with imported LNG (Liquefied Natural Gas). There is a limited amount of natural gas imported from Argentina to supply the old inner city of Concepción. LPG (Liquefied Petroleum Gas) is the principal gas fuel for the remainder of Chile. Marine offloading facilities at Concepción had minor damage, which has been substantially repaired, so that the LPG terminal and bulk storage facilities are now functioning satisfactorily. There was no damage observed in the gas storage facilities in Concepción.

Oil tank sloshing spill over the rim



Refinery plant in Concepcion

Ports

The TCLEE team observed a small portion of the ports affected by the earthquake. The damages are outlined below.

Talcahuano Area

Isla Rocuant, an industrial area of fish processing plants, was almost demolished by the tsunami. The industrial portion of the port was devastated with wave of 4-5 meters high. A fish oil tank was relocated by the tsunami more than 300 meters from its original location. The container-handling portion of the port was not as severely damaged. Depending on orientation relative to the tsunami, some nearby ports suffered only minor damage.

Coronel

Pier 1 at the Coronel Port sustained significant damage to piles; a few piles had welds completely broken from the bottom of the pier deck. Supporting beams close to the abutment were deformed. Damage observed mainly was due to poor soil conditions and permanent ground deformation and lateral spreading. Pier 2 at Coronel was constructed with base isolation design and it had only very minor surface cracks around a few pier heads. The conveyor pier for transporting minerals from ships to warehouses was under construction and only suffered minor damage.

South of the main industrial Coronel Port, a pier used mainly for unloading goods by the fisheries industry was damaged by lateral spreading and was partially collapsed. Furthermore, the power supply cable for the crane at the end of the pier was severed. We understand that this pier will have to be replaced.

Lirquen

The Lirquen Port sustained very minor damage to the piers. Two warehouses in this port sustained extensive structural damage. At the time of our visit, one of the warehouses had been demolished, while the largest one was being repaired. Furthermore, port transportation was affected because the railway tracks were damaged in several areas. The tracks were embedded in concrete and had been snapped longitudinally due to ground deformation. Railway tracks on ties were not damaged.

This fish oil tank was moved 300 m by the tsunami

Fisherman's wharf at Port Coronel

Concrete pier moved towards shore due to lateral spread lateral spread

Pier 1 at Coronel

Pier 1: a few pile supports with broken weld were observed

Pier #2, a base isolated pier-the part of the pier where the cranes are located did not have any damage

Airports

Santiago (Arturo Merino Benítez) International Airport was close for a week due to extensive non-structural elements damage in the passenger terminal building. In the departure hall (about 300 m long by 60 m wide), all the ceiling tiles fell. A few pipes in rest rooms were broken. Light fixtures were damaged. HVAC equipment and ducts were shaken loose from the ceiling and fell. A few glass windows were broken or shaken loose. The only structural damage was the bridge connecting the terminal building to the overpass collapsed. If the earthquake happened during peak occupancy of the terminal, many injuries and casualties could have resulted from these fallen objects.

The mounting pedestal of the steel frame that connects the cab of the control tower to the concrete structure was damaged due to location of anchors too close to the edge of the concrete pedestal. Due to strong shaking the equipment in the cab was damaged. One wood equipment cabinet that was anchored to the concrete floor was sheared off at the base. Only two glass windows were broken. The traffic control has been relocated to secondary control tower until the main tower is repaired.

One at-grade unanchored 1.4 million-liter welded steel water tank collapsed. The water is for fire fighting for the airport, and was full at the time of the earthquake. Tank failure was likely due to repeated wall uplifts, and wall buckling.

Communication to the backup airport Concepción (Carriel Sur) Airport was disrupted, flights cannot be directed to Concepción Airport even if it did not have any problem. The terminal building had water damage due to broken sprinkler system and no one on the night shift knew where to shut off the water until about 7 AM in the morning.

The control tower of this airport had a few panes of glass windows broken and some equipment on the desks fell over. An HF system was dispatched from Santiago Airport as a backup communication system, but before it arrived the communication link was up. There was no commercial flight for 10 days after the earthquake. The airport typically averaged 50 operations (take-off or landing) per day prior to the earthquake. During relief efforts, operations peaked at more than 340 flights a day, placing significant stress on the small crew of 6 qualified air traffic controllers and one supervisor.

There was no damage to the runways, but as a precaution the Instrument Landing System (ILS) was put out of service until recalibrated by a check flight from Santiago.

Santiago Airport control tower damage of the four anchor points of the cab structure

Non-structural damage of Santiago Airport passenger terminal on the departure level (courtesy of Juan Pablo Muñoz)

Roads and Bridges

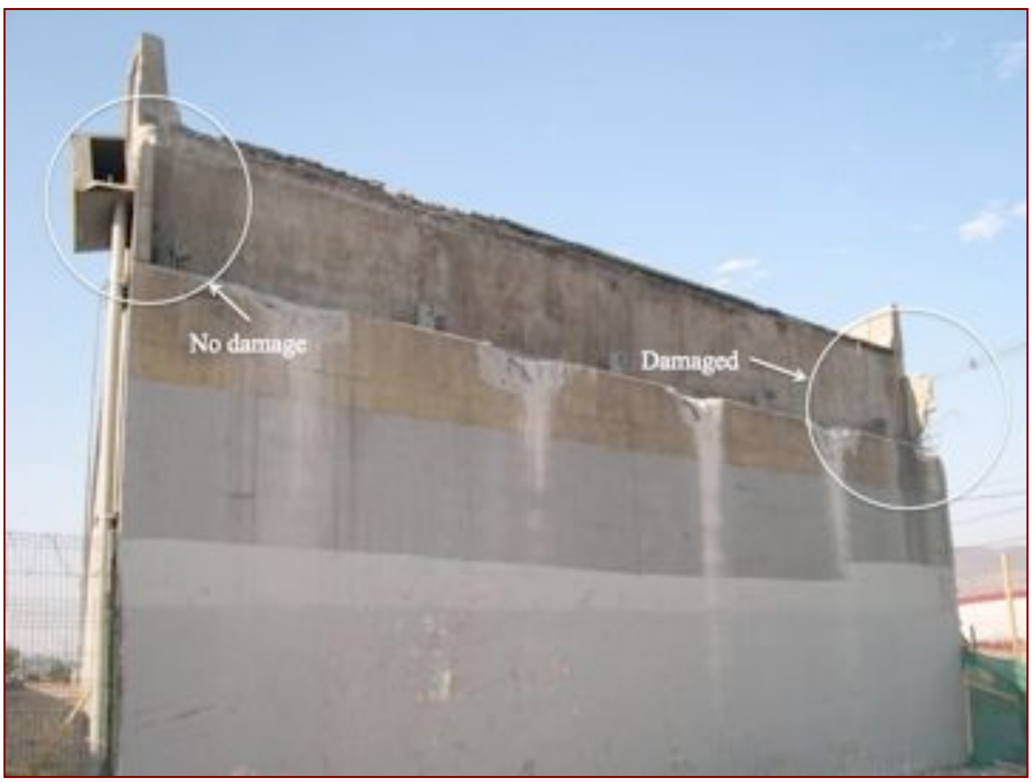
The bridge damage was significant; many bridges should have been designed to provide full serviceability following a major earthquake as experienced in Chile. Many of the bridges failed because of poor detailing at the connections and articulations without the proper attention given to following the load path from the superstructure through the bridge substructure and down to the foundation with capacity protection provided through the load path. New bridges with skewed supports failed and old bridges, adjacent to the failed bridge, with no skew remained standing.

Some of the factors contributing to the observed bridge damage and failures are outlined below:

- Bridges that were designed to be ductile with plastic hinging occurring at selected locations failed prior to the formation of plastic hinging, illustrating the presence of a weak link in the load path.
- Bridges collapsed because of inadequate support lengths and restraint.
- Lateral spreading of the foundations and embankments at the piers and abutments.
- Shear connections failed at the intermediate piers and abutments.
- Skewed supports without proper shear connections and support widths either failed or moved to locations rendering a bridge unsafe to carry traffic loadings.
- Foundation failures due to liquefaction leading to support movements and rotations.

A majority of the road damage caused by the earthquake was a result of poor soil and the lack of subgrade soil treatment during road construction, or badly compacted fills. Soil slumping on the edge of the shoulder and surface cracks were the commonly observed damage to roads and highways in Region VII and Region VIII.

One of the overpasses damaged, this is the highway towards Santiago Airport.



Note the circled areas, showing rotation of the deck.

Railroads

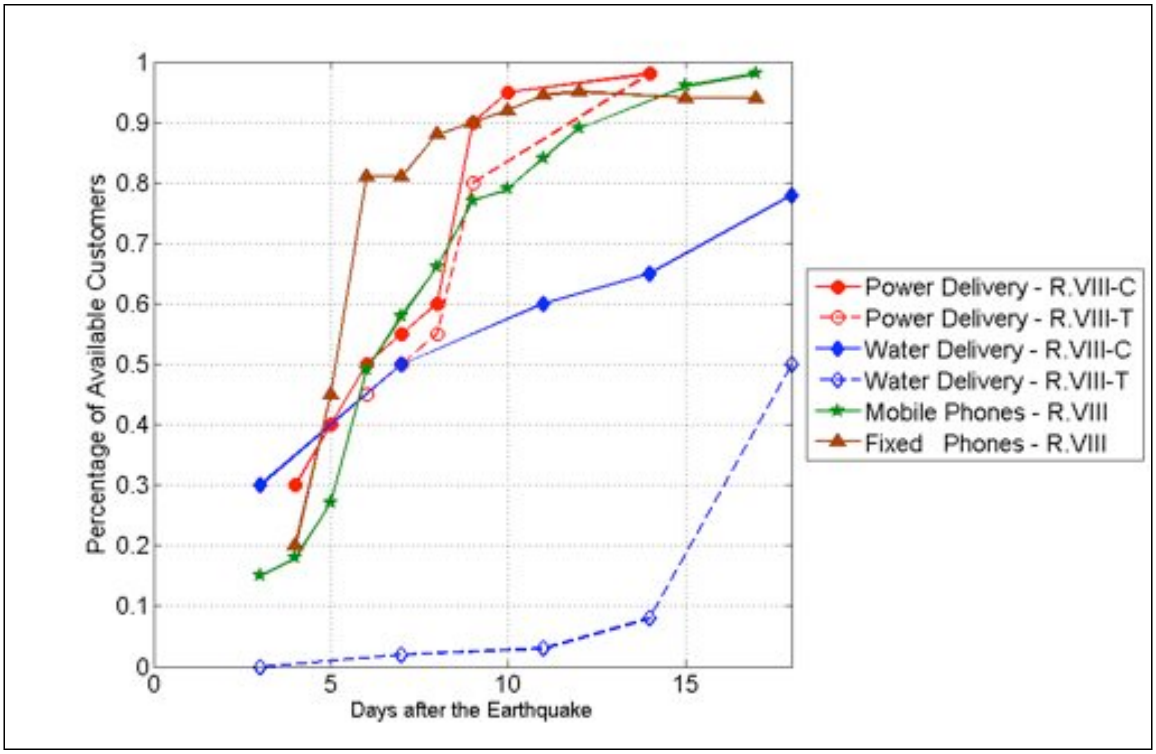
There were minor damage to railway tracks that run along Highway 5. The electric powered cars were not operating due to power distribution system failures. We observed a few sections with fallen poles along the railway track. The TCLEE team visited one of the train station buildings that had been damaged. We understand that several of the older adobe stations in the effected regions will require significant repairs. Train service between Santiago and the south was not operating during our investigation period. However, the commuter trains in Concepción were operating during our visit.

Overhead power line for electric power rail cars failed

Lifeline Interdependence and Resilience

In addition to physical damage observed to lifelines, infrastructure interdependence between power, transportation, telecommunication and water systems increased their loss of functionality or delayed the restoration processes of susceptible and dependent systems. This additional loss of functionality reduced regional resilience, and it was triggered by physical and cyber interaction between lifeline systems, as well as from specific cases of collocation, and from relational and logistical coupling between infrastructures and institutional entities. Specifically, interdependence was strong during the early post-earthquake phase characterized by uncertainty about road network conditions and absence of power availability. This phase had blackouts at the power transmission (> 66 kV) and sub-transmission (13.3 to 23 kV) levels, which led to impacts on the telecommunication systems, mostly mobile communications, because of almost nonexistent emergency power at cell sites beyond batteries whose post-outage operation is only 3-4 hours on average, and impacts on the undamaged portions of the power distribution infrastructure. The water infrastructure had adequate emergency power to operate treatment plants, but the direct damage of the earthquake on water mains and laterals prevented the system from operation. However, the uncertainty on fuel availability, refinery shut downs, and road conditions cast early shadows on the ability of water systems to operate the undamaged and repaired portions of the network during extended power outage durations. In addition, lack of telecommunications may have delayed some of the early hiring, coordination and assignment of water system crews to field repairs, although their availability would have not changed the number of affected customers—only the time to restore their service. Lack of telecommunications during the blackout phase also led to delays in assessing the damage and safety of the power distribution system. This phase had different durations at different regions, but on average for the Concepción area it lasted about 3 days.

The following phase was characterized by the increasing availability of alternate transportation routes, restoration of power at the sub-transmission levels, a steady recovery of telecommunications, water and gas, and an improving but decreasing restoration *rate* of power delivery to customers along main feeders and then laterals, although the consumption base was reduced due to loss of residential and industrial users, mainly in coastal areas affected by the tsunami. The Figure below presents available average data on lifeline system recovery. Note the higher availability of power in Concepcion and Talcahuano alone over telecommunication systems in the entire Region VIII, except for a period at the end of the first week and start of the second week. Such trends provide evidence of functional interaction between power and communication systems. Also note the higher availability of telecommunication land lines over the entire restoration phase, a fact exploited by the utility companies to organize their logistics via fixed telephone access. Finally, the evident direct seismic damage on the water distribution system overshadowed any interdependent effects from power, telecommunications, or transportation of fuel.



Empirical restoration times for power delivery, water distribution, and telecommunications. The letters C and T indicated the cities of Concepción and Talcahuano, respectively. Both cities are in Region VIII, whose capital is Concepción.

Although important underground, overhead, and surface levels collocation cases of infrastructures were observed in the field, only a few materialized into interdependence-induced failures. These specific cases 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 cut operations at collapsed or tagged for demolition buildings, and power distribution overhead lines pulled down at tapping points from collapsed housing facades or entire structures.

In terms of relational interdependence effects from human, institutional, and lifeline coupling, most lifeline systems companies managed to avoid operational personnel deficiencies thanks to reliably available workers supported by food and water provisioning and relatives search programs. However, there was some institutional coupling with detrimental effects in terms of idle time of service companies, such as banks in dense urban areas, which despite having completed internal retrofit projects are not going to receive power and other utility services until demolition of tagged buildings takes place. Such demolition and re-installation of utility infrastructure process can represent business interruption for another 3 to 4 months. Also, as the rate of restoration of most of the different lifeline systems slowed down after the majority of their customers were back on line, the remaining residential and commercial users endured significant inconvenience and indirect losses from direct dependence to lifeline systems, delayed recovery of the local economy and impacted international trade.

Co-located power and telecommunication cables along the damaged Juan Pablo II bridge over the Biobío River in Concepcion.

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