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Lifelines Performance of the Mw 8.8 Offshore BIOBÍO,Chile Earthquake

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Abstract
The paper will provide a summary of all lifelines performance in this strong earthquake. The paper will discuss the damage, emergency response, and recovery of electric power, telecommunication, transportation (roads and bridges), seaports, airports, water and wastewater, and their facilities. The impact as a result of the lifelines service interruption will be discussed; most important is the discussion of lifelines interdependence. Each lifeline will be separated into its own section that presents the failure modes, emergency response, and recovery of service. Each section will end with observations and recommendations.
Keywords: Electric power; Telecommunication; Transportation; Lifeline; Failure mode; Recovery; Interdependence

1. General Geotechnical Aspects

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 [1, 2]. This earthquake, which was located offshore at 35.909°S, 72.733°W with a depth of 35 km and had a plate rupture area of about 550 km by 150 km, shook a large region with an estimated 80% of Chile’s population, Figure 1. The epicenter is located 335 km SW of Santiago the capital of Chile and 105 km NNE of the coastal city of Concepción. Numerous large aftershocks occurred over the months, including more than 130 magnitude 6 or higher aftershocks within the following week. 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 (sub ducting) at a rate of about 70 cm per year. Chile has a long history of large earthquakes, including great subduction zone earthquakes of magnitude 8 or larger. 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 of Chile, 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 over 60 seconds of strong shaking and a recorded maximum 0.65 g peak ground accelerations (PGA) in the Concepción area. Modified Mercalli Intensity (MMI) of VIII was Experienced in a number of coastal and inland communities, Figure 1. The geologic conditions of this area 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, there were fewer occurrences of landslides and ground related failures due to liquefaction, lateral spreading, and bearing capacity. Some areas in Concepción were subjected to focusing of high seismic energy as well as ground motion amplification due to soft soils.

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Ground shaking and geotechnical related ground failures impacted all lifelines and resulted in damage to buildings, bridges, highways, railways, and ports, and interruption of transportation, water and wastewater, gas and liquid fuel, electric power, and telecommunication services, as well as contributing to lifeline interdependence and coupling issues. Areas with engineered soils including industrial facilities on wetland sites, retaining walls and ground improvement appeared to perform well.

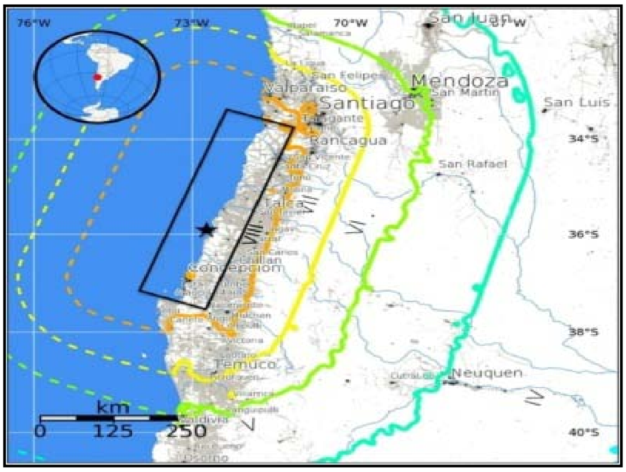

Fig. 1. MMI contours and the area of the rupture zone (150 x 550 km). (Source: USGS)

2. Electric Power System

The distribution of source of electric power generation in Chile is 22.7% coal, 24.6% oil, 7.90% gas, 5.30% biomass, and 39.50% hydro. During the dry summer season hydropower output is usually lower and the demand for electricity is higher. Therefore many large facilities have their own backup power generation to maintain business operation continuity. Some large apartment units in Santiago have backup power generator to handle possible brown outs.

There was minor damage to power generation plants in the impacted area. Hydro power plants had no reported damage, as they are all located away from the coast in the lower Andes.

Transelec and CGE are the two major power service providers that serve the earthquake-impacted area. Most of the distribution systems in this area are operated by CGE, while high voltage transmission is by Transelec.

2.1. Transmission System

The transmission network performed reasonably well and was ready to energize 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 North America, Chile makes extensive use of pantograph disconnect switches and candlestick live-tank circuit breakers, which are used sparingly in the earthquake zones of North America, Figure 2. More than 25 failures occurred but that these failures represented a small percentage of the inventory. A couple of towers crossing Biobío River collapsed.

Fig. 2. Candlestick style disconnect switch (Kwasinki photo)

Over the last 25 years, the backbone 220 kV and 500 kV systems were designed with earthquake provisions of 0.30g PGA. These systems were 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 for the coastal communities that experienced higher levels of ground shaking (PGA = 0.2g to 0.45g) suffered sporadic damage.

2.2. Distribution System

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 (Maule) and Region VIII (Biobío). One power company had to replace 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. Most of the distribution system damage was a result of building collapse where drop wires were severed or buildings damage the poles.

Two weeks after the earthquake, the distribution system service was restored. Figure 3 shows a typical damage to the distribution system.

2.3. Observations, Recommendations, and Interdependence

While there were exceptions, good seismic installation practices, such as equipment anchorage and slack in conductor connecting equipment were done very well.

The underground distribution cable network worked well. Other power companies in neighboring countries provided restoration resources, most likely through disaster mutual support agreement.

Fig. 3. Typical power distribution system damage

The results demonstrated that establishing a credible seismic installation practice will reduce losses in hardware and service.

Electric power outage was the main cause of many BTSs (Base Transceiver Stations) out of service, which had a cascade effect on restoration of water and wastewater systems, power distribution system, and train services.

3. Telecommunication

All service providers, both landline and wireless services, experienced extensive setbacks due to commercial power outages, unanchored equipment failures, building failures, and loss of reserve power in most distributed network facilities (BTSs, small remote switches, and digital loop carrier (DLC) remote terminals). Only critical offices-Central Offices (COs) over 5000 subscribers, MTSOs (Mobile Telephone Switching Offices), and fiber backbone carrier offices have backup power generators. Both landline system and wireless system were restored within 7 days after the earthquake.

3.1. Landline System

Although fiber optic cables were severed in many locations due to co-locating on bridges and overpasses and permanent ground deformation, alternative links provided by other companies allowed a limited number of transmission circuits for inter LATA (local access and transport area) operation. However, with increase in call volume and reduction of circuits many calls could not be completed.

Close to 200 outside plant DLC (Digital Loop Carrier) or DSLAM (Digital Subscriber Line Access Multiplexer) remote terminals were affected mostly due to lack of power. Close to 150,000 landline subscribers were affected as most of them were connected to small remote offices with less than 5,000 subscribers. Again it was due to power problem as none of these sites have backup power generators and with only a few hours of battery power.

In one CO a backup generator failed due to transfer switch malfunction, which was used to power the air conditioner. This caused overheating of electronic components that resulted in equipment failure.

CO equipment damage, backup generator malfunction, battery damage, and power outage resulted in sporadic service disruption. Figure 4 shows switching equipment damage in a CO in Concepción. Landline system was restored within three days after the earthquake and most of the fixes were temporary. Full restoration will need months.

Fig. 4. Switching equipment damaged in a CO in Concepción

3.2. Wireless System

About 70% to 80% of the cell sites in Regions VII and VIII had problems with either equipment or antennas damage. This rate falls to about 50% in Region V (north of Region VII). Equipment in BTSs is not anchored, Figure 5. COs and MTSOs have seismic designed equipment. Fallen perimeter walls or nearby structures collapse affected operation in many BTS sites. Collateral damage to BTS antennas occurred in many locations, Figure 6.

There were many logistical problems in order to refuel BTSs with permanent generators or at sites where portable generators were deployed. Some of the generators were provided by affiliated companies outside of Chile. Diesel supply was difficult to ensure, although some service providers had 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.

3.3. Observations, Recommendations, and Interdependence

Collocated facilities damage happened in most earthquakes, redundancy and dispersed routes should be developed to reduce the loss of service. Anchoring equipment is one of the lowest cost practices to reduce equipment damage. Either extend the battery power supply duration or provide backup generator power should be considered in all BTSs.

BTSs are usually located in strategic sites that are difficult to access particularly after a strong earthquake due to damaged roads and bridges. It is critical to install power generators in these sites.

Fig. 5. Unanchored equipment in BTS

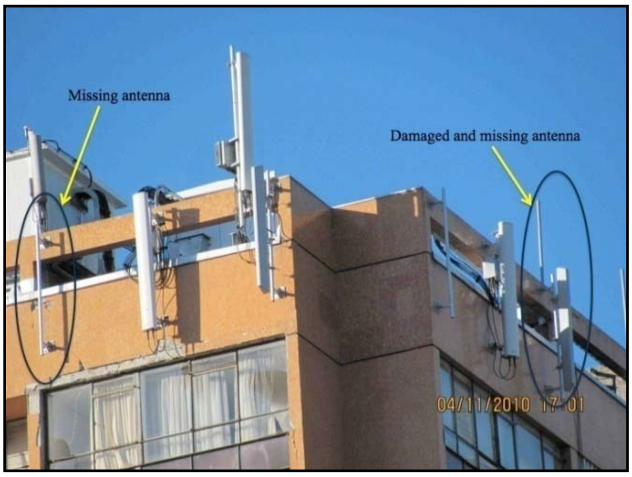

Fig. 6. Collateral damage to BTS - the building is condemned

Many service providers (such as water, power, emergency response, airports, etc.) depend on telecommunication to restore service or to coordinate restoration efforts. The loss of cellular systems had impacted utilities that rely on cellular phones as communication tool to repair crews. Utilities shall use their own radio system as their basic communication tool while cellular phones are used as a backup.

4. Transportations

The transportation system sustained significant damage, however the recovery was quick considering the size of this event. Except for the north-south rail transportation system, all other transportation systems were temporarily repaired within a week.

4.1. Roads and Bridges

Both roads and bridges damage were significant. More than 300 bridges in the earthquake-impacted area sustained various degree of damage. Along Hwy #5 there were 5 collapsed bridges between Santiago and Chillan, Figure 7 shows a collapsed bridge along Hwy #5. Even in Santiago there were a few overpasses collapsed. Almost all bridges in the tsunami areas were destroyed. In Concepción the three main bridges that cross Biobío River were damage, one was open using a bailey bridge for the collapsed section, Figure 8. The other two were closed to traffic causing congestion during rush hours.

About 110 locations of roads sections were damaged, not including the roads in tsunami impacted area. 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. Detours in many locations were easily put in place to provide service.

Fig. 7. Hwy #5 bridge collapse, south of Linares

4.2. Rail System

There was minor damage to railway tracks that run along Highway 5, Figure 9. The electric powered cars were not operating due to power distribution system failures, Figure 10. A few sections of the railway track had fallen power poles. One of the URM train stations was damaged. It was reported that several of the older adobe stations in the effected regions require significant repairs. Train service between Santiago and the south was not operating in April two months after the earthquake. However, the local commuter trains in Concepción were operating.

Fig 8. Juan Pablo Bridge - bailey bridge installed as a temporary fix

Fig. 9. Damage to railway track (Eidinger photo)

4.3. Airports

4.3.1. Santiago International Airport

Santiago (Arturo Merino Benítez) International Airport passenger terminal building was close for a week due to extensive non-structural elements damage on both floors, the departure and arrival floor. In the departure hall (about 300 x 60 meters) about 90% of the ceiling tiles fell, Figure 11. A few pipes in washrooms were broken. Many overhead 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 two catwalks connecting the terminal building to the overpass collapsed, Figure 12. If the earthquake happened during peak occupancy of the terminal, many injuries and casualties could have resulted from these fallen objects.

Fig. 10. Damage to power poles for railway trains (Eidinger photo)

The mounting pedestal of the steel frame that connects the cab of the control tower to the concrete structure was damaged; the anchors were too close to the edge of the concrete pedestal, Figure 13. 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 the secondary control tower until the main tower is repaired.

The airport was open to a limited number of passenger flights two days after the earthquake. Tents were used as temporary immigration and customs inspection points, and airline check in counters. A major airline reported that two weeks after the earthquake, it was operating only 50% of the normal number of inbound and outbound flights.

Fig. 11. Non-structural damage inside Santiago International Airport terminal (Public Works Chile photo)

4.4. Concepción International Airport

Concepción (Carriel Sur) International Airport is designated as the backup airport for Santiago. Unfortunately, communication to Concepción International Airport was disrupted and flights could not be directed to Concepción International Airport even if it did not have any problem. The Concepción International Airport 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. That resulted in water damage to equipment and escalators within the terminal building. A few glass panels and doors were broken

Fig. 12. Damage of overpass connected between the terminal and the raised access road (Public Works Chile photo)

Fig. 13.Control tower cabin anchor points damaged due to short edge distance

The control tower of this airport had a few panes of glass windows broken (Figure 14) and some equipment on the desks fell over the counter top. An HF communication system was dispatched from Santiago International 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 and landing) per day prior to the earthquake. During relief efforts, operations peaked at more than 340 operations per day, placing significant stress on the small crew of 6 qualified air traffic controllers and one supervisor for two weeks.

Fig. 14. Broken glass windows of Concepción (Carriel Sur) International Airport control tower (Public Works Chile photo

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

4.4.1. Los Angeles Airport

This is a small commuter flight airport that serves the Los Angeles area. It was close to all flights except relief supply flights. According to the airport director, the airport will not be open until the control tower and the terminal building are fixed. There was extensive damage to the control tower (Figure 15). The terminal building a wood construction and the damage was limited to glass on door and windows. A few light fixtures were damaged.

Fig. 15. Los Angeles Airport control tower

4.5. Sea Ports

4.5.1. 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 (Figure 16). A fish oil tank was relocated by the tsunami more than 300 meters from its original location (Figure 17). 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.

Fig. 16. Fish processing plant damaged by tsunami

4.5.2. Coronel Port

Pier 1 at the Coronel Port sustained significant damage to piles that are close to the shoreline; a few piles had welds completely broken from the bottom of the pier deck (Figure 18). Supporting beams close to the abutment were deformed. Damage observed mainly was due to permanent ground deformation and lateral spreading.

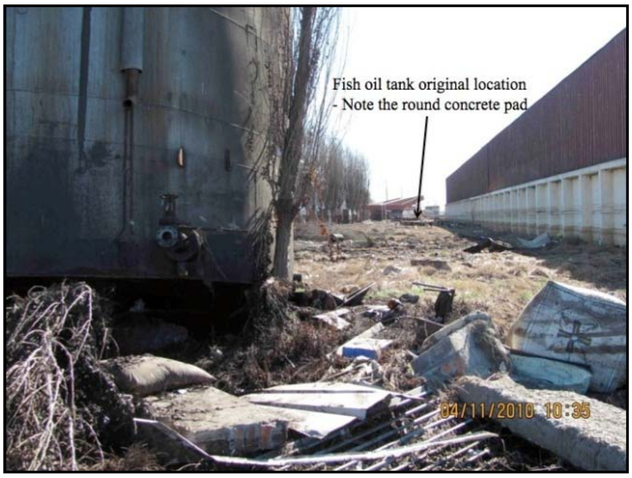

Fig. 17. Fish oil tank relocated by the tsunami

Pier 2 at Coronel was constructed with seismic 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 Coronel Port, a pier (Lo Rojas) mainly used by the fisheries industry was damaged by lateral spreading and was partially collapsed (Figure 19). The power supply cable for the crane at the end of the pier was severed. It was reported that this pier would be replaced.

Fig. 18. Coronel Port pier #1 - pile with weld broken off

4.5.3. Lirquen Port

The Lirquen Port sustained very minor damage to the piers. Two warehouses in this port sustained extensive structural damage. In April 2010, one of the warehouses had been demolished, while the largest one was being repaired (Figure 20). Cargo transportation was affected because two railway tracks that routed through the undamaged warehouses were severed in several locations. The severed rail tracks were embedded in concrete and had been snapped longitudinally due to ground deformation (Figure 21). Railway tracks on ties were not damaged.

Fig. 19. Fishman pier damaged

Fig. 20. Damaged warehouse being fixed

4.6. Observations, Recommendations, and Interdependence

Failure of many bridges may be due to insufficient detailing of joints to develop a load path to the super structure and eventually to the foundation. New bridges with skewed supports failed and old bridges, adjacent to the failed bridge, with no skew remained standing.

Poor soil and the lack of subgrade soil treatment during road construction, or badly compacted fills were the main causes of many road failures.

Many bridges should have been designed to provide full serviceability following a major earthquake as experienced in Chile.

Non-structural elements in airport terminals should be installed with good seismic designs to prevent damage that cause disruption.

At Coronel Port good seismic design demonstrated reduce business interruption.

Transportation systems are coupled to economic well being of a country, mitigation efforts should continue in these systems to reduce losses.

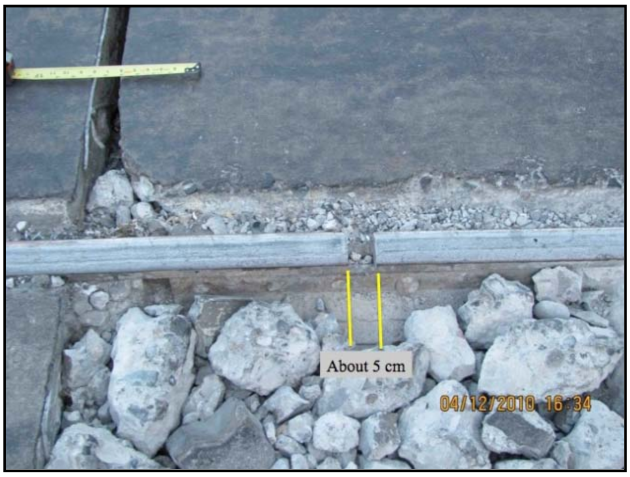

Fig. 21. Severed rail track

5. Gas and Liquid fuel

Santiago is supplied with imported LNG (Liquefied Natural Gas). There is a limited amount of natural gas imported from Argentina via pipelines 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 had been repaired. The LPG terminal and bulk storage facilities were functioning satisfactorily after the repair. There was no damage observed in the gas storage facilities in Concepción.

5.1. Refinery

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 not related to the operation of the facility and restarted 10 days after the earthquake when safety check was completed. The capacity of this refinery is about 98,000 bpd (barrels per day). The refractory in the heaters room fell to the heater floors in Biobío refinery near Concepción precluding the use of the heaters. There was minor damage to pipes, and other structures in the plant. Therefore Biobío refinery was shut down after the earthquake.

Due to liquefaction and lateral spreading along the beach, one of the two steel crude oil pipelines that feed into the refinery failed. 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 bpd.

5.2. Tanks Farms

Tank sloshing occurred in floating roof tanks with resulting spillover of product (Figure 22). One floating roof tank developed a leak due to local ground failures.

An unanchored 1.4 million-liter welded steel water tank collapsed at the Santiago International Airport due to sloshing (Figure 23). 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.

5.3. Observations, Recommendations, and Interdependence

The damage to the gas and liquid fuel system was light. The refinery closures were precautionary measures to ensure production plant safety. It is a good practice to carefully inspect all elements within a refinery prior to starting production after a strong earthquake. Safety procedures must be developed and put in place to deal with post earthquake situations. Periodic exercise is also an important part of safety. Both electric power and telecommunication played an important role in the recovery of the plant.

Fig. 22. Oil leak along the top edge of tank

Shortage of fuel slowed down the recovery of the telecommunication system that required backup generator to power the equipment during power outage.

6. Water and wastewater systems

Information of water system performance was provided by Essbío Water Department in Region VIII. Essbío also provided the information relating to the Rural Potable Water Systems, and Santiago Potable Water System. Most of the damage occurred in Region VIII.

Fig. 23. Water tank for fire fighting – Santiago International Airport

6.1. Water System

Essbío provides potable water to about 4 million people of communities in Concepción area. Each community has its own system that is not interconnected. The potable water systems include about 7,000 km of transmission and distribution pipe. There are 1,200 km of pipes in the city of Concepción.

The heaviest damage of Essbío water systems was concentrated in Concepción and Talcahuano. Pipe breaks were caused by strong ground motion in firm ground area and by lateral spread and settlement in the river bank areas. In tsunami-impacted areas, damaged sea wall and buildings led to damage buried pipelines.

Damage to the Concepción area water treatment plant included:

severe damage to intake structure due to a combination of lateral spreads and ground shaking,

i) internals damage to four clarifiers (baffles, settlers and supporting elements),
ii) damage to suspended ceilings in control room, and water quality laboratory,
iii) toppling of computer monitors and computers in control room, and
iv) toppling of water quality test equipment and glassware from countertops.

In the Concepción area distribution system, there were 72 breaks and leaks to large diameter welded steel pipes (Figure 24). As of mid-April 2010, about 3,000 repairs had been made to smaller diameter pipes. Prior to the earthquake, the net leak rate was about 40%. The leak rate in April 2010 was about 60%.

Over the past 50 years, the government of Chile has constructed nearly 2,000 elevated potable water tanks in small rural areas country wide, of which about 420 were in the strong earthquake areas. At least 73 of the elevated tanks completely collapsed (Figure 25). Failures were due to inertial overloads.

The Santiago water system includes two large water treatment plants on the east side of the city. Potable water outages in the Santiago area were sporadic and many areas had no outages.

Fig. 24. Broken steel water pipe (Essbio)

6.2. Wastewater System

Wastewater systems in Concepción sustained heavy damage. The wastewater treatment plants experienced structural damage due to inertial overload. The large diameter interceptor pipes, and small diameter collector pipes were broken due to permanent ground deformation. Prior to the repairs were completed, the untreated wastewater was discharged to the river.

Fig. 25. Collapsed water tank (Eidinger)

6.3. Irrigation System

Water canals and hydraulic structures are used in many areas to deliver water from the Andes to communities in the central agricultural areas for irrigation purposes. As of April 1, 2010, the status was US$ 2M emergency repairs and US$57M projected long-term repairs. As many as 42 facilities were initially categorized as in extreme emergency condition, 32 facilities in serious condition, 25 collapsed, 38 with various levels of structural damage, 1 overflowed, and 2 ruptured. It was unclear whether any one of these facilities had any impact on hydropower generation.

6.4. Observations, Recommendations, and Interdependence

One fire was reported in the Concepción after the earthquake. The fire happened in the Chemical Laboratory of Concepción University, which was burned down (Figure 26). Many research works were destroyed. The lost of water supply might be the cause of the total destruction. There were two other fires reported that had been set by people. Loss of electric power and telecommunication resulted in longer duration to restore service as the utility people use cellular phones (that was not functional for 7 days) to dispatch service crews.

The utility should have their own communication system such as radio instead of relying on the cellular phone system that is not under their control.

7. Lifelines Interdependence

In addition to physical damage to lifelines functional interdependence between electric power, transportation, telecommunication, and water systems has significant impact on the recovery and restoration processes of these individual systems. The loss of functionality due to co-location has been recorded in many earthquakes since the ASCE post earthquake investigations started in the early 1970's. Physical and functional coupling between lifelines becomes an important element in developing resilience in post earthquake performance from a functional point of view.

Fig. 26. Burned down chemical laboratory of Concepción University (Concepción University)

Immediately after the earthquake the effect of interdependence becomes prominent among roads/highways, electric power, and telecommunication. Damaged roads and highways hindered recovery of the electric power distribution system to speed up telecommunication damage restoration. Economic impact to businesses due to power outage and lose of telecommunication was an important coupling that was observed in Chile. This will take at least a few months when the power and telecommunication system completely return to normal condition.

In this earthquake, co-located equipment such as antenna, power cables, and pipelines in damaged buildings, collapsed buildings and bridges demonstrated system vulnerability to service interruption.

8. Conclusions

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 and the relatively short duration of lifeline services interruption 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.

9. Acknowledgments

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- Yumei Wang (geotechnical, geology & tsunami)

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