Maule, Chile M_w 8.8 Earthquake of February 27, 2010

By: John Eidinger, G&E Engineering Systems Inc. Copyright 2010.

The Chile M_w 8.8 subduction zone earthquake on the Nazca plate struck central and southern Chile on February 27, 2010 at 3:40 am (local time). The fault rupture area was approximately 500 km (north to south) by 100 km (west to east). The northernmost extent of fault rupture was near the City of Rancagua, or about 50 km south of Santiago; the southernmost extent of fault rupture was near the City of Temuco, about 550 km south of Santiago.

Seismicity

Figure 1 shows the tectonic plates in the region and the location of the epicenter at latitude -36° 17' 23", west longitude 73° 14' 20" and depth 30.1 km. The Nazca plate is moving eastward at about 8.4 cm/year. The Nazca plate has produced many moment magnitude 8+ events, including the 1960 M 9.2 (southern Chile, 2001 M 8.3 (central Peru) and the recent 2010 M 8.8 (central Chile). Return periods for these M 8+ interplate events along the Nazca plate are on the order of 100 to 300 years.

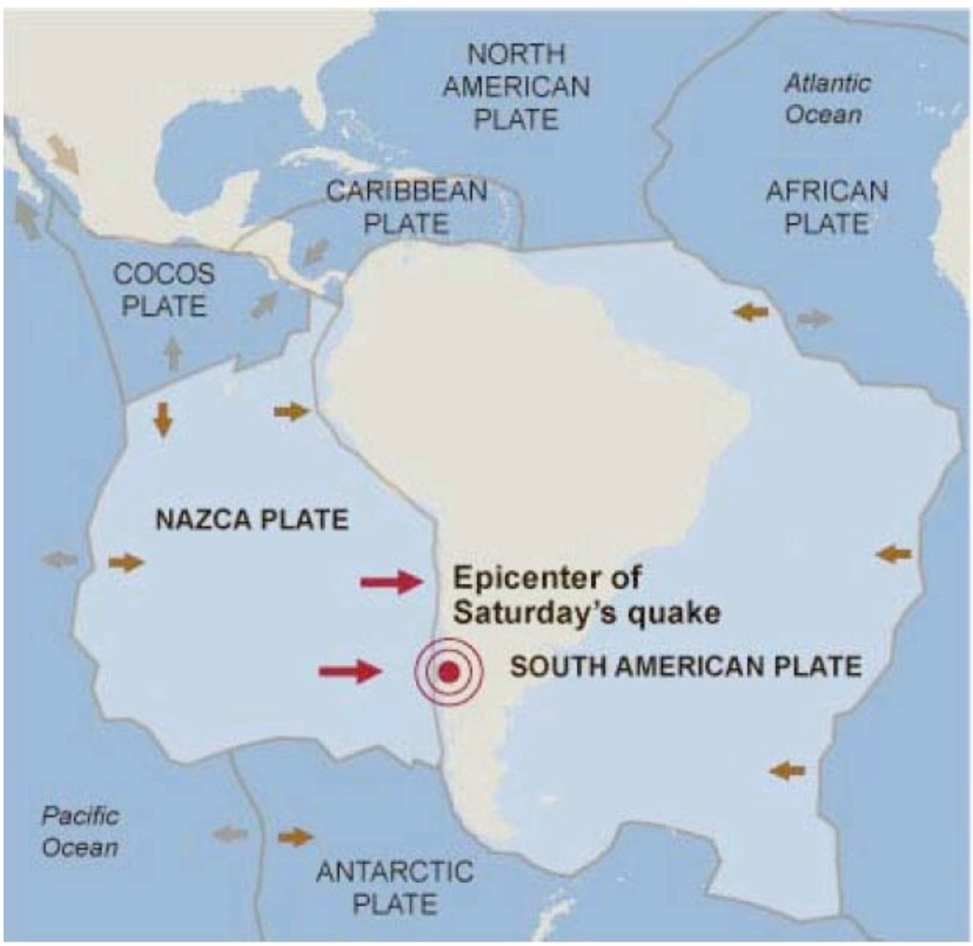

Figure 1. Regional Plate Tectonics

The 1960 M 9.2 event prompted Chile to adopt seismic code provisions for newer construction. Figure 2 shows the seismic zone map for Chile: Region 3 (along the Pacific Ocean coastline, including the Cit of Concepcion) is called zone 3; the central valley of Chile (including the capital city of Santiago) is set at zone 2; and the high Andes mountains to the east is set at zone 1. The equivalent design provisions for firm soil sites are horizontal peak ground acceleration of 0.4g (zone 3); 0.3g (zone 2) and 0.2g (zone 1).

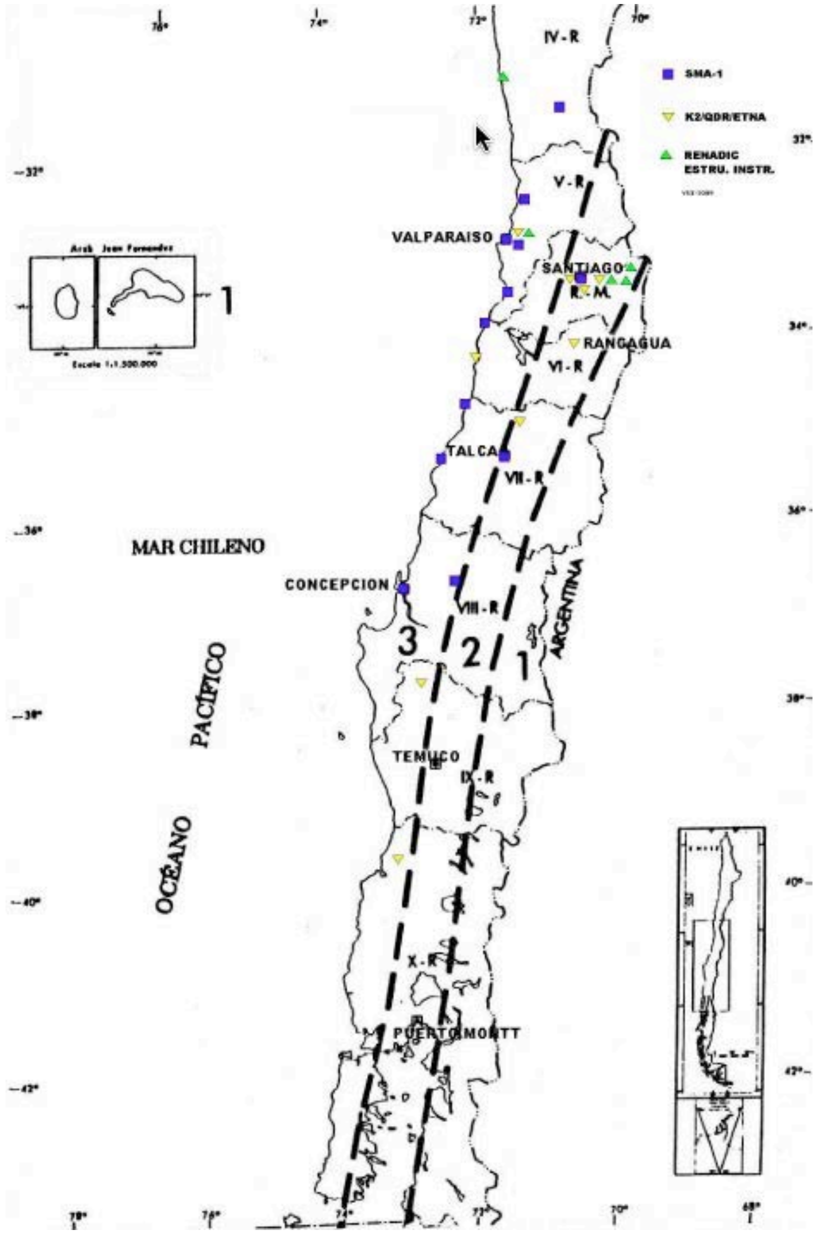

Figure 2. Seismic Zone Map of Chile

Figure 3 shows that the 2010 M8.8 interplate event filled in a zone between the 1985 event to the north, and the 1960 event to the south. Prior cycle M7+ events occurred in 1939, 1928 and 1906.

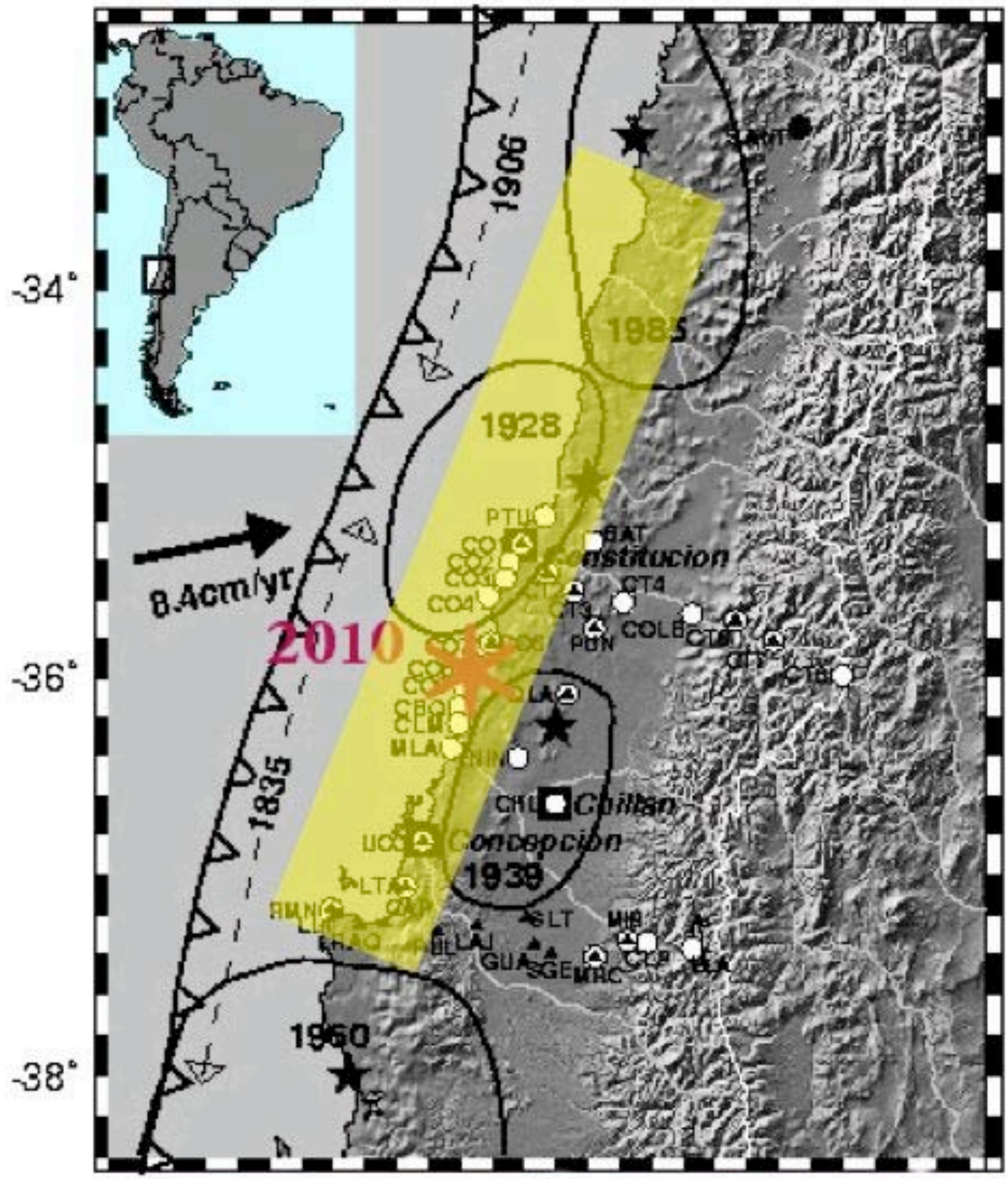

Figure 3. Location of 2010 Event (Yellow Zone depicts rupture area)

Figure 4 shows a cross section, looking northerly, of the 2010 event. The cities with the closest distance to the rupture were Talcahuano and Concpecion, about 25 km; both these cities are located along the Pacific Ocean, with Talcahuano being a northern suburb of Concepcion. The typical distance for cities in the central valley of Chile was 60 km, including Los Angeles, Talca and Chilean.

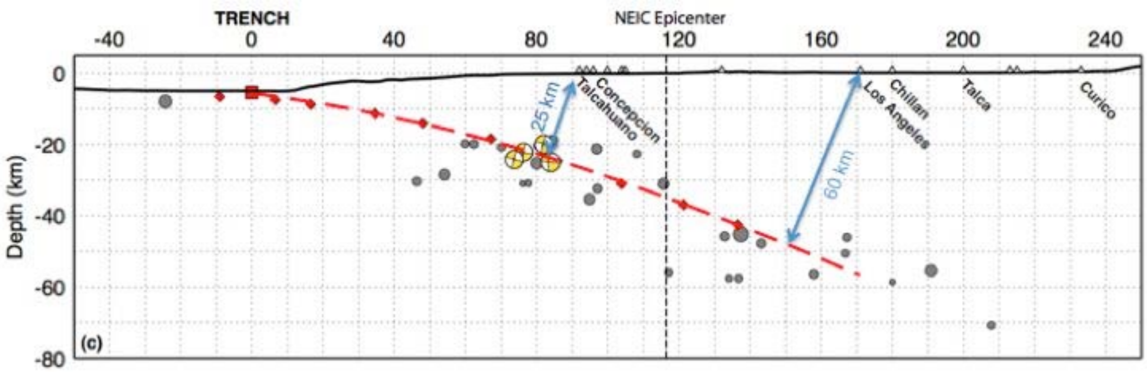

Figure 4. Cross Section of Fault Plane

Ground Motions

The country of Chile is divided into 15 regions, commonly referred to using Roman numerals I through XV, plus the capital region of Santiago.

The regions of the country most affected by the earthquake (either directly over or directly east of the ruptured plate) were Region VI (northern extent of fault rupture, including the cities of Rancagua, San Fernando, Talca), Region VII (including the cities of Curico, Talca and Constitucion), and Region VIII (including the cities of Concepcion, Chillan, Los Angeles), and Region IX (southern extent of fault rupture, including the city of Temuco). Along the coast of the Pacific Ocean is the city of Concepcion (population over 1,000,000 people), and the mid-sized cities or towns of Constitucion, Talcahuano, Coronel, Lota and Lebu.

The population situation directly over or just east of the rupture zone is about 4,500,000 people, the bulk of whom experienced horizontal ground motions between PGA = 0.15g (firm soil conditions at the east foothills of the Andes) and 0.40g (firm soil conditions at the Pacific Ocean). Local variations in ground motion would be about -50% to +100% of these values.

The University of Chile[1] maintained a set of strong ground motion instruments. The uncorrected PGA maxima are listed in Table 1 and the corrected (bandpass filtered) velocities in Table 2. The highest two recordings were on rock sites (0.6g, 0.9g). Above the rupture zone, horizontal PGAs at firm soil sites were commonly 0.25g to 0.45g. The U. de Chile recording at Concepcion contains a lot of long period motion (T = 1.5 to 2.2 seconds), suggesting a soft soil site; most of the remainder of the instruments reflect firm soil conditions.

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[1] Boroschek, R., Soto, P., Leon, R., Maule Region Earthquake, February 27, 2010 Mw = 8.8, University of Chile, Faculty of Mathematics and Physical Sciences, Civil Engineering Department, Report 10/08, August, 2010.

Station	Region	Azi-muth	PGA NS g	PGA EW g	PGA Long g	PGA Trans g	PGA Vertical g
Copiapo	III	0	0.030	0.016			0.008
Vallenar	III	0	0.020	0.019			0.010
Papudo	V	60			0.295	0.421	0.155
Vina del Mar Marga-marga	V	0	0.351	0.338			0.261
Vina del Mar Center	V	0	0.219	0.334			0.186
Valparaiso, UTSFM	V	180			0.224	0.266	0.146
Valpariaso, Almendral	V	310			0.137	0.304	0.080
Llolleo	V	340			0.319	0.564	0.702
FCFM	Santiago	0	0.165	0.163			0.138
Center	Santiago	270			0.218	0.309	0.182
Maipu	Santiago	0	0.561	0.478			0.240
Penalolen	Santiago	0	0.295	0.293			0.280
Puente Alto	Santiago	0	0.265	0.263			0.130
La Florida	Santiago	0	0.236	0.165			0.130
Matanzas	VI	0			0.342	0.308	0.234
Hualane	VII	0			0.389	0.461	0.390
Curico	VII	150			0.470	0.409	0.198
Talca	VII	0			0.477	0.424	0.244
Constitucion	VIII	0			0.552	0.640	0.352
Concepcion U.de.Chile soft soil site	VIII	60			0.402	0.284	0.398
Concepcion U de Concepcion Rock site	VIII						
Angol	IX	0	0.928	0.681			0.281
Valdivia	XV	0	0.092	0.138			0.051

Table 1. Peak Ground Accelerations (g) (Uncorrected)

Station	Region	Azi-muth	PGV NS Long cm/sec	PGV EW Trans cm/sec	PGV Vertical cm/sec	Spectral Dominant Hz Period (Seconds)
Copiapo	III	0				0.3 - 0.4
Vallenar	III	0				0.25 – 0.95
Papudo	V	60	16.7	24.8	6.1	0.3
Vina del Mar Marga-marga	V	0	37.9	44.6	12.2	0.35 - 0.85
Vina del Mar Center	V	0	20.9	32.6	13.3	0.5 – 0.8
Valparaiso, UTFM soft	V	180	7.4	16.0	9.4	0.2
Valpariaso, Almendral	V	310	29.2	22.3	10.7	0.7 – 0.9
Llolleo	V	340	25.8	31.0	22.3	0.25
FCFM Lee	Santiago	0	15.6	22.0	15.7	
Center	Santiago	270	21.9	25.6	14.4	
Maipu	Santiago	0	44.1	39.0	21.8	
Penalolen Hospital Oriente	Santiago	0	29.3	22.7	15.3	
Puente Alto Hospital Sotero del Rio	Santiago	0	24.6	31.5	16.2	
La Florida Mirador Station Metro	Santiago	0	19.2	17.9	12.4	
Matanzas	VI	0	43.4	27.8	15.7	0.5
Hualane	VII	0	38.8	35.0	26.2	
Curico	VII	150				0.2
Talca	VII	0	27.4	33.4	19.1	
Constitucion	VIII	0	43.3	68.6	20.5	
Concepcion soft	VIII	60	67.3	51.7	26.7	1.5 – 2.2
Angol rock	IX	0	34.3	37.6	12.2	0.2
Valdivia	XV	0	13.6	18.4	6.6	

Table 2. Peak Ground Velocity (cm/sec) (Corrected)

Immediately north of the most strongly-shaken regions are Region V (Valparaiso along the coast) and the capital of Santiago, towards the east. The population of Santiago is about 5,500,000 people. These regions experienced ground motions typically between PGA 0.20g to 0.30g, but again locally with variations of -50% to +100% or more of these values.

Geotechnical Considerations

In addition to the effects of ground shaking, buried water system pipelines are strongly affected by local geotechnical effects, including liquefaction, landslide and surface faulting.

We observed no evidence of surface faulting; this is as expected, as there is no land-based surface rupture in this event.

While there was evidence of landslides (deep seated) in rural areas, we observed no evidence of landslides in major urban areas. The topography of Chile is similar to California, with coastal hills at the Pacific Ocean, a flat central valley, and high mountains to the east. There were few landslides observed in the strongly shaken coastal hills, and none in the Andes. The paucity of landslides might be attributed, in part, to the time of year of the earthquake (February 27), which corresponds to the end of the dry season; had the earthquake occurred in the wet winter season (say August), there may have been more landslides triggered.

There was widespread evidence of liquefaction along the coastline of the Pacific Ocean as well as along the banks of the rivers that empty into the Pacific Ocean. Liquefaction effects were particularly common in Concepcion, and towns and locales along the Pacific Ocean within 50 km north and 150 km south of Concepcion. Perhaps 30% of river banks in these areas showed clear movement, form a few inches to a few feet laterally, with some vertical settlements. The geology along these areas is commonly alluvial, with sands and silts. At 14 ports visited, nearly all sea walls showed evidence of rotation (a few did not), with corresponding damage to piers and wharves, as well as buried infrastructure immediately on the landward side of these facilities. Bridge abutments at the sides of rivers were commonly tilted or otherwise damaged where there was evidence nearby of liquefaction. A few bridge piers within rivers showed evidence of settlement (under 5% of all piers). Where liquefaction occurred, there were severe effects to buried water pipes and other buried infrastructure, as will be discussed in following sections.

Subsidence and land uplift also occurred. This effect is due to the rebound of the South American Plate as it is released along the interplate zone. Areas in the western side of the rupture zone uplifted; areas east subsided. This type of ground movement is not thought to be of general concern to buried pipelines, and the ground curvatures are not high enough to materially stress buried pipe. However, these uplift and subsidence effects are important for ports and harbor areas, as they change the sea level and effect the ability of shipping traffic to pass through shipping channels.

This earthquake also caused tsunamis. The tsunamis impacted the City of Constitucion and an island in the river adjacent to Constitucion, resulting in many fatalities in those areas. Tsunamis also inundated the port of Talcahuano, resulting in widespread damage to fish factories and port facilities in that important commercial area. Tsunamis are not known to have directly inundated any water treatment, wastewater treatment or buried water / wastewater pipes.

Water Systems

There are two water companies that deliver potable water to the majority of the cities in the strong shaking area. Aguas Andina is the water company that serves the Santiago region. Essbio is the water company that operates individual water systems serving the cities of Rancagua, Curico, Talca, Chillan, Concepcion, Talcahuano, Coronel, Los Angeles, and Temuco. In addition to these two large companies, there are several hundred small rural water systems developed by the Chilean government (ministry of public works, MOP). MOP also maintains many canals throughout Chile. The following summarizes the major performance issues for these water systems.

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 water systems include about 7,000 km of transmission and distribution pipe, of which 3,500 km are in Region VIII, of which 1,200 km are in the city of Concepcion.

By far the largest amount of damage to the various Essbio water systems was concentrated in Concepcion and the adjacent community of Talcahauno. Figure 5 shows a plot of the restoration of potable water service for these cities. This plot was developed in conjunction Essbio, and reflects a preliminary assessment. Water restoration in the Concepcion region was to over 99% of customers able to take water by the first week of April, 2010.

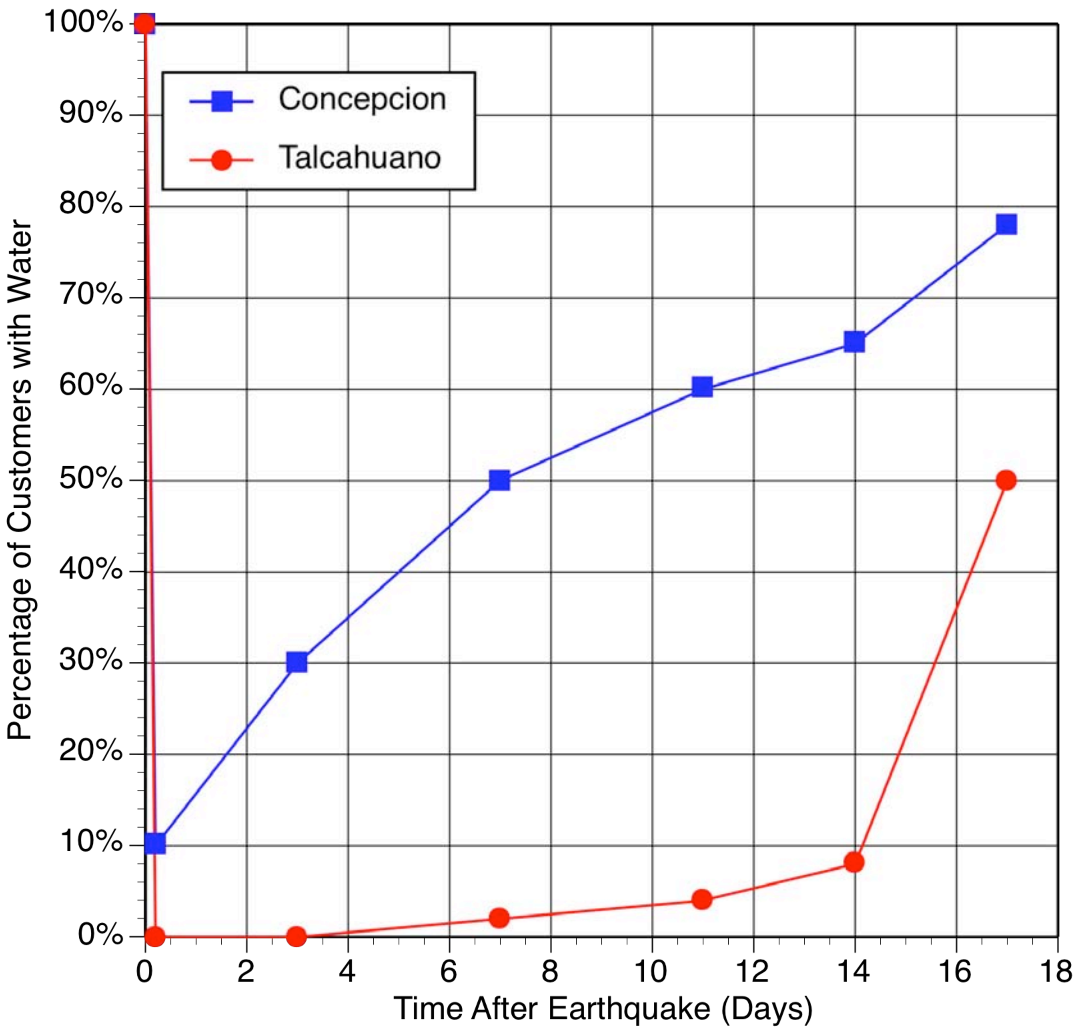

Figure 5. Water Restoration

Figure 6 shows a schematic diagram of the potable water system serving Concepcion and Talcahuano.

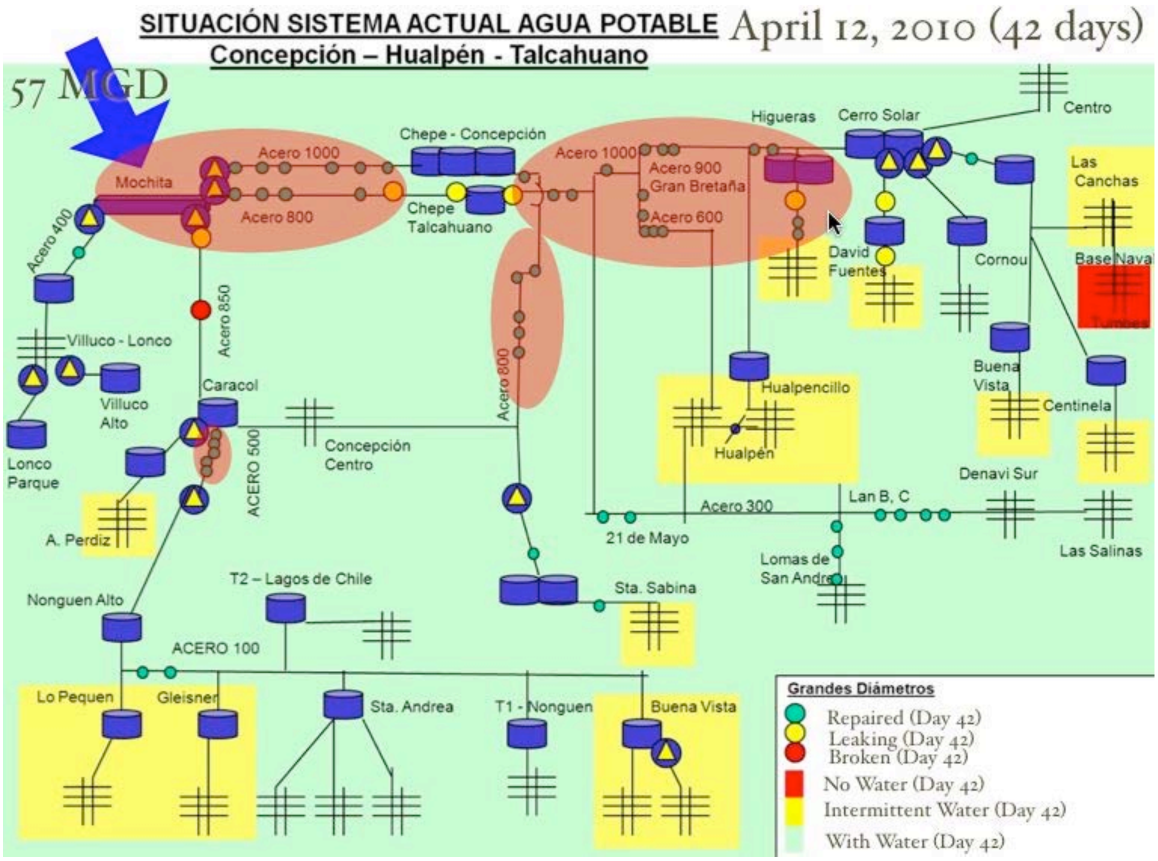

Figure 6. Schematic Diagram for Concepcion and Talcahuano Water Systems

The Concepcion water system includes one water treatment plant (Mochita WTP, estimated PGA = 0.30g to 0.40g), a large pressure zone serving the downtown and nearby low-elevation areas of Concepcion, and a variety of small pressure zones serving hilly terrain. Figures 6 and 7 show the major facilities and pipelines in the water system. In both Figures 6 and 7, red zones indicate areas that experienced liquefaction with corresponding damage to large diameter (16" to 40" diameter) pipes. The small circles in Figure 6 show the schematic locations of individual breaks of larger diameter welded steel water pipes. The solid red zone in Figure 6 schematically shows the continuing water outage at the Naval base just north of Talcahuano. (Note: in Figure 6, "Acero" means welded steel pipe, and diameters are listed in millimeters).

By examining Figures 6 and 7, one sees that every major transmission pipeline from the Machito WTP to the downtown area (heading easterly or northerly) suffered damage immediately after the earthquake. A smaller residential area east of the WTP was able to get water as soon as the emergency generator at the WTP was activated, about 45 minutes after the earthquake.

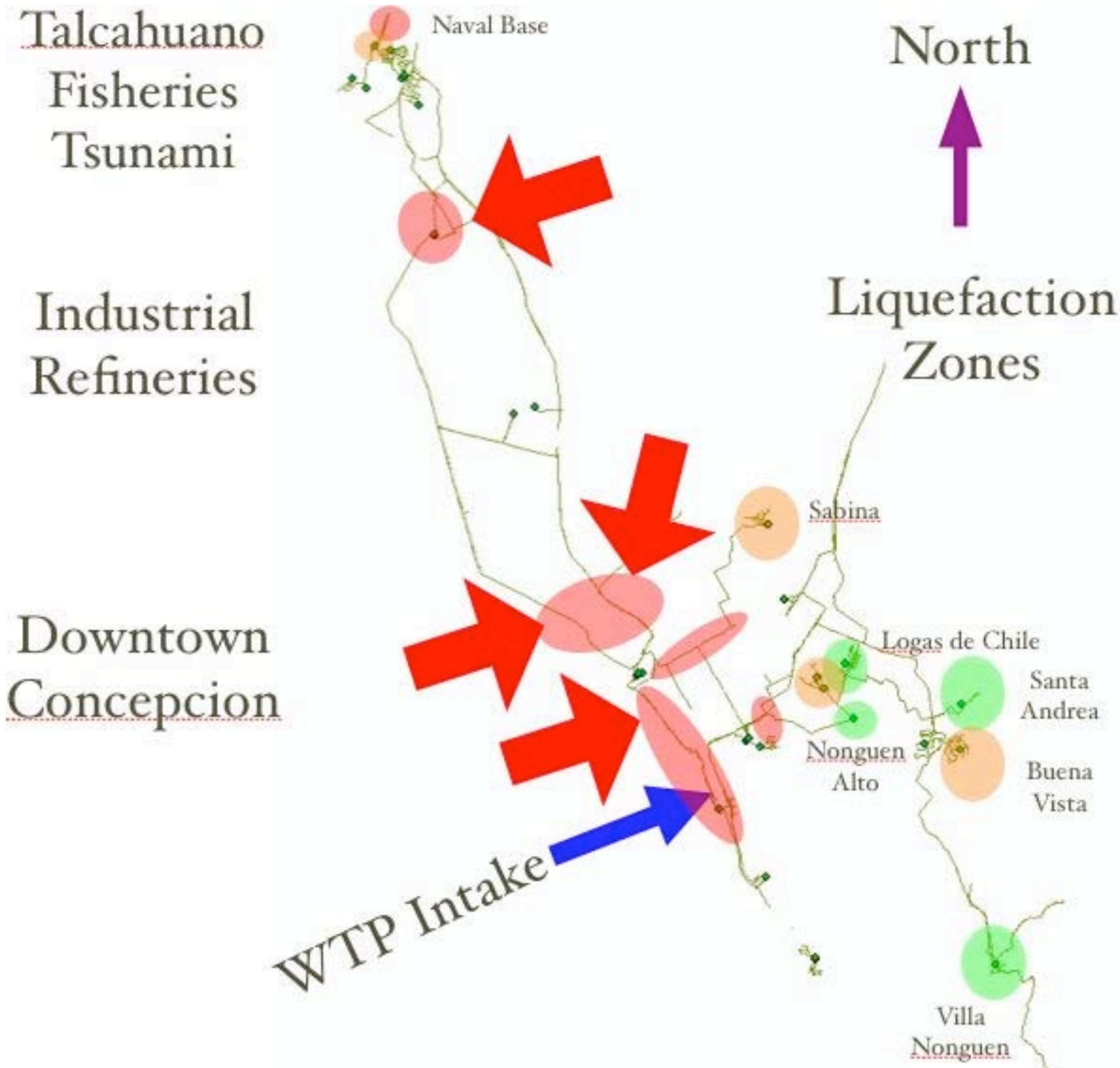

Figure 7. Map of Major Pipes and Liquefaction Zones, Concepcion and Talcahuano

The WTP has a raw water pump station that takes surface water from the Bio Bio River, treats it via four clarifiers (settling, flocculation), and filters, and then pumps it into the main pressure zone. Plant capacity is 2.5 cubic meters per second (57 million gallons per day, MGD). Disinfection is by chlorination.

The raw water pump station includes a reinforced concrete structure supporting trash racks, and a reinforced concrete wet well that is below the pump station floor, housed in a reinforced concrete frame structure with some infill unreinforced brick panels (several damaged, Figure 8). The trash rack structure underwent about 1 foot of lateral spread and 1 inch of settlement, due to liquefaction at the shore of the river inlet. The wet well and pump station structure above did not move permanently, thereby resulting in a 13-inch wide space between the buildings. The pump station building suffered extensive damage, but did not collapse; to protect the pumps, steel "catch" structures were built after the earthquake to protect the pumps, and the pump station building was shored up and laterally braced after the earthquake.

Water leaves the pump station to one of four circular clarifiers. For all four clarifiers, the center post, each set of baffle rings and many tube settlers were damaged or dislodged by sloshing / water loads (Figure 9). As of 6 weeks after the earthquake, one of the four clarifiers was being repaired; while the three others remained in service (albeit with short-circuits and lower efficiency).

The water then goes to the 16 filters. None of the filters suffered permanent damage. All pipes in the filter pipe gallery remained leak-tight and undamaged.

The desktop monitors in the control room all fell (6 of 6), of which 2 broke. All 6 desk-top "tower type" computers also fell from the desktop to the floor (all 6 worked after the earthquake). About one-third of all glassware and countertop components in the water quality laboratory fell to the ground (most broke). About half the desktop equipment in the water quality lab slid off countertops and fell to the floor; most fallen pieces of equipment broke. A suspended ceiling fell. Underground large diameter water pipes within the plant boundary broke.

The treated water transmission lines leaving the WTP are welded steel, commonly 500 mm to 1000 mm diameter. There were 72 failures in these pipes; Figure 10 shows one such example, showing a wrinkled steel pipe with tear and leaking water. Most of the failures appear to be attributed to settlements and lateral spreads. See Figures 27 to 33 for additional examples of damage to large diameter transmision pipes.

The distribution system pipes (commonly 150 mm to 300 mm) include Cast Iron pipe (oldest areas in Concepcion), Asbestos Cement (common material during the growth of the community), PVC or HDPE. Today, in 2010, all new distribution pipes are either PVC or HDPE. The Concepcion water system includes about 1,200 km of pipe. Through April 12, 2010, repairs were made at about 3,000 locations, of which about 1/3 were to pipe mains, and 2/3 to service laterals (up to the customer's meter). See Figures 37 to 40 for typical examples of repairs to distribution pipes.

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%.

On February 27, 2010, (after the earthquake), 17% of Essbio's customers in Region VIII (including Concepcion, Talcahuano and other cities) had piped potable water. By April 12, 2010, this was increased to 97%. Factors contributing to the water outages and restoration time were broken pipe; mobilization of a large pipe repair crew; nearly complete loss of cellular phone service for several days (Essbio had no private radio system). Loss of offsite power was problematic, but the WTP's diesel generator was turned on 45 minutes after the earthquake, and was sized to operate the entire plant at 50% capacity. There were also failures of a few potable water tanks in the distribution system, and outages as pump stations to small pressure zones did not have permanent generator sets.

Preliminary evaluations show that the bulk of pipe damage was due to permanent ground deformations (PGDs) induced by liquefaction. Recently installed fusion-butt welded

HDPE pipe suffered no pipe failures, demonstrating that this type of pipe can be very effective for accommodating substation ground failures.

On February 27, 2010, Essbio was able to provide piped potable water service for 40% of its customers in Region VI, 25% in Region VII, and 17% in Region VIII; with the largest outages in Concepcion. By April 10, 2010, Essbio was able to provide piped water service for 100% of its customers in Region VI, 100% in Region VII, and 99.5% in Region VIII.

The last area in Region VIII to get potable water service restored will likely be the small community of Arauco, with 2,000 customers. This seaside town was totally damaged by the earthquake, with PGDs damaging the water infrastructure as well as the other built environment.

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. The common system uses a well with submersible pump (about 100 to 600 feet deep, depending on the local aquifer), an elevated water tanks (commonly a steel tank atop steel braced structure, with tank storage volume of about 10,000 gallons), and PVC distribution pipe. In Regions VI, VII and VIII, at least 73 of the elevated tanks completely collapsed. Tank failures were due to inertial overloads.

The three most common styles of elevated tanks are concrete tanks on concrete cylindrical support structures (somewhat common) or steel tanks on steel cross-braced structures (very common), or concrete tanks on concrete frame structures (least common). The larger volume tanks (up to about 500,000 gallons) were all concrete. As mentioned before, the elevated steel tanks on steel structures suffered many collapses. We observed dozens of elevated concrete tanks, of which only one had collapsed (it was on a concrete frame-support structure).

Figure 11 shows a common elevated steel tank (undamaged). It is estimated that there are more than 1,000 nearly identical tanks situation throughout rural Chile. Figure 12 shows the steel tank resting (it is welded, but the welds cannot be seen in the photo) on a steel beam; and one of the four tubular column-upper frame connections; it is suspected that this bolted beam-to-column connection was the weakest link that led to the many collapses. Figure 13 shows one of the 73 collapsed tanks. It was reported that in a few cases the collapsed tank damaged nearby structures with casualties due to the impacts. We obtained conflicting data as to the total number of such tanks that collapsed; we verified 73, but one official indicated the total was over 400. In any case, we estimate that most (more than 75%) of these types of elevated steel tanks collapsed, if they experienced ground motions of PGA much over 0.25g.

The restoration of water service in the rural areas was done as follows: the systems with collapsed tanks were identified; regional power was restored to the well; if the tank had collapsed, the tank was isolated from the water system; for systems with damaged tanks, the well was operated in direct mode to the distribution system. Prior to the earthquake, essentially none of the 1000+ rural water system had emergency generators.

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). The bulk of Santiago is built on firm soils or thin soils over rock, and PGAs ranged from about 0.10g (eastern hilly areas) to 0.35g (southwestern areas); locally ±50% of these values. Potable water outages in the Santiago area were reported to be sporadic, and not concentrated in any specific geographic area; many areas had no outages. While there was widespread evidence of minor to moderate damage to many buildings in Santiago, as well as some building collapses, there was no widespread evidence of liquefaction in the Santiago area. The lack of liquefaction is the primary reason for the relatively good performance of the water system in the Santiago area.

Santiago Airport Water Tank

There are four large liquid fuels and one water tank located at one site the Santiago Airport. All five tanks are welded steel. The tank site is located in Chiles "seismic zone 2", which translates to a seismic design level motion of PGA = 0.30g.

The water tank collapsed, while the adjacent four liquid fuels tanks remained intact. (Figures 14, 15, 16). The water tank had a storage capacity of 1,300 m^3, or about 340,000 gallons. The water tank had the following (approximate) dimensions: diameter 50 feet, height to overflow level 23.5 feet, wall thickness of lower course lower steel course wall thickness = 5 mm. Computed internal hoop stress due to water pressure is about 16,000 psi, which is within the typical range for allowable stresses for common design of steel water tanks.

The concrete tank rests on a concrete at-grade ring beam. The tank was unanchored. Water pipes were attached to the tank at the lower course. The steel roof was supported by beams. There was ample evidence of internal corrosion to the steel at and near the roof level, while the outside of the tank was painted and did not appear to have much corrosion.

The observed failure modes appeared to be tearing of the bottom course from the steel floor plate, with a nearly uniform tear vertically along one of the vertical seam welds in the lower courses (Figure 16). This led to collapse of the tank, with subsequent buckling and tearing of the steel.

The uplifted floor plate seen in Figure 15 (about 3 inches of permanent vertical uplift) strongly indicates that tank wall uplift occurred during the earthquake. For unanchored at-grade steel tanks, this is expected performance.

We would not normally expect this type of performance (gross collapse) for a well-built and well-maintained steel tank in a magnitude 7 earthquake. The possible root cause(s) for the observed failure are as follows:

- Tank wall uplift leading to tearing of the bottom course – floor plate welds. This is the most likely cause of failure. This clearly demonstrates the fallacy of assigning R = 3.5 to 4.5 for unanchored steel tanks (implied by all AWWA D100 code versions since the early 1970s) coupled with long duration of ground shaking.

- Accumulating corrosion could have weakened welds and steel plates. We observed a modest amount of corrosion on the exterior of the tank. The interior of the tank appeared to have a fair amount of corrosion below the water line, and major corrosion above the water line.

- Once the tank wall-floor plate tore due to a combination of wall uplift (repeated cycles) and wall buckling, the tear likely propagated up a vertical full penetration weld. With the tearing of the tank wall, the high rate of release of water through the vertical tear would have caused the gross opening up and movement of the wall, leading to further tearing of the wall-floor plate around much of the circumference (Figure 15).

- Improper penetration of welds in vertical full-penetration welds. This would be a quality control issue during original construction. We do not have enough original design information or close-up inspection of the failed welds and accumulated corrosion to validate this hypothesis.

- Very high local ground motions (say PGA > 0.8g or so). We have no local site instrument to provide this information, but the apparent modest levels of damage to four (partially filled) liquid fuels tanks and pump station building suggests that the local level of ground motion was not more than PGA = 0.25g to 0.35g.

We were unable to gain access to carefully inspect the performance of the nearby liquid fuels tanks. However, their observed (from the site boundary, about 100 feet from the tanks) minimal damage suggests that they were designed at the same time as the water tank, using the same paint system and same staircase designs. The lack of damage to the somewhat larger (taller) liquid fuel tanks to the water tanks suggest that possibly they were no more than 50% full at the time of the earthquake, a not uncommon practice.

Wastewater Systems

Wastewater collection is provided by local communities. Essbio has a large collector pipe that take the raw sewage to a wastewater treatment plant in Concepcion.

On February 27, 2010, Essbio was able to provide piped wastewater service for 92% of its customers in Region VI, 85% in Region VII, and 43% in Region VIII; with the largest outages in Concepcion. The primary causes of the wastewater outage in Concepcion were the failure of the main collector pipe due to imposed lateral spreads / PGDs, and damage to baffles to the primary treatment tanks at the WWTP. This resulted in direct discharge into the Bio Bio River.

There was damage to a large diameter wastewater pipe in Los Angeles, resulting in direct discharge into the Quilque River.

The last region to get wastewater service restored in Region VIII was likely about 4,500 customers in Talcahuano – Ifarle. In this area, wastewater was temporarily discharged into the Ifarle Canal as the earthquake and tsunami destroyed a wastewater pumping plant and the main grid of collector pipes in this area.

By April 10, 2010, Essbio was able to provide piped wastewater service for 99% of its customers in Region VI, 98% in Region VII, and 75% in Region VIII.

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. These facilities were designed and are maintained by the MOP. As of April 1, 2010, the status of these facilities was as follows:

- 98 facilities in the strong shaken area (43 in Biobio Region VIII, 26 in Maule Region VII, 13 in Santiago, 7 in O'Higgins, 5 in La Araucania, 3 in Valpariaso, 1 in Los Rios.
- $ 2,111,000 (US$) for emergency repairs.
- $57,700,000 (US$) projected for long term repairs.
- 42 facilities categorized initially as being in an extreme emergency condition.
- 32 facilities categorized initially as being in a serious emergency condition. For example, damage to concrete linings in canals.
- 16 facilities categorized initially as being in a moderate emergency condition. For example, minor damage that can be repaired under normal maintenance.
- 25 facilities collapsed; 38 had structural damage (ranging from light to extreme); 3 had non-structural damage (ranging from moderate to extreme); 1 overflowed; 2 ruptured (extreme); 8 had cracks (either extreme or serious); 2 were undermined; 19 had other types of damage.
- 69 canals. Being evaluated for long term solution.
- 7 canals. Being repaired.
- 14 canals. Repaired.
- 5 canals. Under design.

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 (no local military bases, and travel by road was nearly impossible due to bridge damage); after which crown control was restored, often at gunpoint. The need for safety for Essbio staff and contractors, as well as the loss of communications, led to a slowdown in restoration efforts of at least several days.

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 (requiring fire department response) or fire spread occurred.

Essbio has a permanent staff of about 500 people. Essbio uses outside contractors for nearly all pipe work, with common support of about 500 contractors. Prior to the earthquake, Essbio had 4 pipe repair crews. After the earthquake, Essbio retained additional pipe repair crews, reaching 70 crews system-wide during the peak pipe repair effort.

After the earthquake, to offset the los of piped potable water supply in many areas, Essbio installed 900 1,000 liter tanks in affected zones to provide potable water to local communities. These 1,000 liter tanks would be filled up at the water treatment plant, then trucked out to a suitable point in the distribution systems. People would take water from these tanks as needed, via small hose bibs, and filling customer-supplied cannisters. Essbio did not "man" these sites; instead, water usage was self-administered by the local residents.

Raw water turbidity in the Bio Bio River spiked after the earthquake, but returned to normal within a few days. The spike was not much different than would be expected in a winter storm, and so did not have much influence on water quality.

The cell phone network in Concepcion suffered general failure, taking about 5 days to restore. Essbio normally uses cell phones for communication with staff and contractors, and had no private radio system. The lack of communications slowed down the restoration of water service, perhaps by 3 to 5 days overall.

Summary

Potable water outages in Concepcion were widespread and lengthy. Most of this was attributed to non-seismically-designed pipe failures due to PGDs. At least 73 elevated water storage tanks in rural water systems collapsed. Damage to baffles and settling tubes in clarifiers was common. Use of unreinforced brick / masonry / adobe infill walls contributed to structural damage of water treatment plant buildings, as well as office buildings. Non-structural damage occurred to desktop computers, laboratory equipment and suspended ceilings. Lack of up-to-date emergency response and preparedness plans, spare parts, emergency generators, repair crews, heavy equipment, with coincident failure of the cellular phone network, general chaos in the community in the first few days after the earthquake, all led to a slowdown of restoration of service.

Figure 8. Collapsed Wall at Mochita WTP Raw Water Pump Station.

Figure 9. Repairs being made to Clarifier at Mochita WTP

Figure 10. Damaged Large Diameter Welded Steel Water Pipe

Figure 11. Typical Elevated Small Steel Tank (Constructed 2006)

Figure 12. Column – Frame Connection (Constructed 2006)

Figure 13. Typical Collapsed Elevated Small Steel Tank (Constructed 1999)

Figure 14. Collapsed Water (Foreground Left) and Nearby Liquid Fuels Tanks at Santiago Airport

Figure 15. Collapsed Water Tank at Santiago Airport

Figure 16. Roof-Wall-Staircase Connection of Collapsed Water Tank at Santiago Airport

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Appendix

This appendix provides additional photos of damage to water and wastewater systems.

Mochita WTP

Figure 17 shows settlement at the Mochita WTP that led to damage of a u-shaped concrete water channel.

Figure 17. Collapsed Water Tank at Santiago Airport

Figure 18 shows damage to the baffles at one of the four clarifiers at the Mochita WTP. Some tube settlers are displaced in the background. There was similar damage to all four clarifiers.

Figure 18. Damaged Baffles at Mochita WTP

Figure 19 shows the damage to the pump station at the Mochita WTP. The building uses non-structural infill walls (some cracked) and has non-ductile concrete columns. While the building did not collapse, there was much concern that it might subsequently collapse in an aftershock. Should the building collapse, it would damage the motors and pumps within, leaving Concepcion without any source of water. Accordingly, Essbio installed steel braces and "catchers" around all the motors (Figure 20) to assure that a subsequent building collapse would not impact the equipment.

Figure 19. Damage to the Pump Station at Mochita WTP

Figure 20. Installed Steel Braces and "Catchers" over Pump Station Motors

Figure 21 shows 14 "one ton" chlorine tanks at the Mochita WTP. These are locate within a steel building. None of the tanks were anchored, and we could observe no evidence of sliding of the tanks on their wood skid supports. Plant staff confirmed that there was no sliding of the tanks. Had ground motions been PGA of 0.60g or larger, there would almost certainly have been some sliding of the tanks. While there was no strong motion instrument near the WTP, we relied on observed evidence to estimate the actual motions. Given the various levels of damage to non-structural items (like bookcases, windows, suspended ceilings, etc.) we estimate the actual horizontal PGA at the site to have been about 0.30g to 0.45g.

Figure 21. Chlorine Tanks at Mochita WTP

The filter building showed no evidence of structural or nonstructural damage. Figure 22 shows the operating deck floor; none of the control panels had sliding or damage to components within. The building style is reinforced concrete roof supported on columns and beams. We did not observe cracking in the structure. The filters boxes, immediately outside the windows in Figure 22, were not known to have any leakage post-earthquake; nor was there damage to the launders.

Figure 23 shows the pipe galley directly beneath the operating floor seen in Figure 22. There were no leaks ot any of the large diameter pipes or damage to any valve or control. Along both sides of the filter gallery are two-level rod-hung cable trays. These cable trays have no lateral supports as would be required by the non-structural provisions of the ASCE 7, IBC, NBCC, SMACNA, NSF13 codes and guidlines; this strongly suggests that these and similar code provisions that proscriptively require lateral bracing of cable trays, conduits, pipes at ~10 foot spans, needs to be re-written. Note in Figure 23 that by providing some flexibility in the cables from the trays, the trays can swing laterally during the earthquake without imposing any distress on the rod hangers or the electrical cables.

Figure 22. Filter Building Operating Floor

Figure 23. Filter Building Pipe Gallery

Figure 24 shows a partially fallen suspended ceiling at the WTP. The fallen tiles and materials had no life safety consequences, and the plant operators who were on shift at the time of the earthquake reported no egress issues. This suggests that code provisions to require "seismic design" for suspended ceilings as a "life safety" requirement are not entirely logical. Instead, it would make some sense to improve these types of ceilings over critical areas (such as control rooms, and using proper seismic detailing), while accepting lower cost suspended roof installations in other areas (warehouses, etc.). For "life safety", it would appear sufficient to add wires to heavier items in roofs to prevent them from falling on people below. For locations where there are potential sprinkler pipes that have sprinkler heads through the suspended ceiling, the pipe-ceiling interaction needs to be considered, as impacts of the ceiling with some types of sprinkler heads can snap off the heads leading to unwanted water release and damage. In the USA, a wire-hung suspended ceiling might cost about $3 per square foot to install; test data shows that modern code provisions for "seismic" suspended ceilings (wire diagonals plus compression struts) provides little or no capacity much beyond PGA = 0.4g or so. The cost to build truly "seismic" suspended ceilings with complete lateral load paths with load rated components can easily cost 10 times the basic cost of a suspended ceiling. Given the cost and performance issues, and the common observation that suspended ceilings tend to fall apart at about PGA – 0.30g to 040g or so, suggests that the current codes and state of practice in the USA are resulting in extra cost for "seismic bracing" without delivering much in the way of extra seismic performance; for those interested in good performance of suspended ceilings, it is suggested that a qualified engineer verify the complete load path of the ceiling system.

Figure 24. Damaged Suspended Ceiling

The diesel generator for the WTP is shown in Figure 24. Note the unrestrained startup batteries on the left. The steel skid rests on spring isolators, one of which became dislodged during the earthquake. According to plant staff, the offsite power went out almost immediately after the earthquake; the plant operator turned on the emergency generator 45 minutes after the earthquake; the generator started on demand.

In the USA, we would recommend that the startup batteries be properly restrained (there were not for this generator), and put in suitable "snubbers" to restrain the isolated generator. Neither of these improvements were in place at the time of the earthquake, yet the generator performed as required, even if a isolator was damaged. This suggests that the level of ground motion was not over PGA = 0.50g, as the batteries would almost certainly have slid / toppled. Still, the relative low cost to restrain batteries (usually under $200) and snub a generator (usually under $2,000) seems like a good practice for such a vital piece of equipment at a WTP.

Figure 25. Emergency Generator at Mochita WTP

Figure 26 shows some of the nearly 900 plastic tanks used to distribute potable water in and near Concepcion after the earthquake. The tanks would be filled at the Mochita WTP and then truck-driven and dropped off at a suitable distribution point.

Figure 26. Plastic Tanks Used for Water Distribution

Water Transmission Pipes

Figures 27 to 33 show some examples of damaged large diameter water pipes in Concepcion.

Figure 27. Wrinkled Steel Pipe

Figure 28. Erosion due to Large Diameter Pipe Failure

Figure 29. Failure of two Parallel Steel Pipes at Same Location (date stamp incorrect)

Repairs are being made to two steel pipes. Temporary manholes are cut; the pipes aligned with external bars; and then custom-made butt straps installed. Common repair times for a crew, per steel pipe were on the order of 48 hours (working 24 hours shifts) (not including disinfection or repairing the road).

Figure 30. Repair Effort for Two Parallel Failed Steel Pipes (date stamp incorrect)

Figure 31. Repairs Completed (date stamp incorrect)

Figure 32. A broken ~36" diameter gate valve (flange failure) within a concrete vault was resolved by removing the valve and replacing it with a straight piece of pipe. The lack of spare valves, parts and the urgent need to restore water supply led to this type of repair.

Figure 32. Broken Gate Valve and Pipe Repair in Vault Remnants

Figure 33. Another Pipe Break (date stamp incorrect)

Wastewater Treatment Plant

Figure 34 shows damage to the baffles at a clarifier at the Concepcion Wastewater Treatment Plant (WWTP). Figure 35 shows damage to the external concrete walls of the clarifier.

Figure 34. WWTP Clarifier Damage

Figure 35. WWTP Clarifier Damage

Figure 36 shows the pull-apart of the concrete walls in the chlorine contact tank at the WWTP. There were liquefaction-caused PGDs at the WWTP. The level of damage at the WWTP suggested that it would take about 6 months to bring the plant back in service. One of the main sewers bringing raw sewage to the plant was broken, near the Bio Bio river, so there was no influent to the WWTP, and raw sewage was flowing into the river.

Figure 36. WWTP Chlorine Contact Tank Failure

Distribution Pipes

Figure 37 to 40 show typical repairs to common distribution pipes (6" to 8" common). The style of repair of using pipe clamps, inserting PVC pipes, etc., shows the range of damage and repair strategies.

Figure 37. Pipe Repair

Figure 38. Pipe Repair

Figure 39. Pipe Repair

Figure 40. Pipe Repair