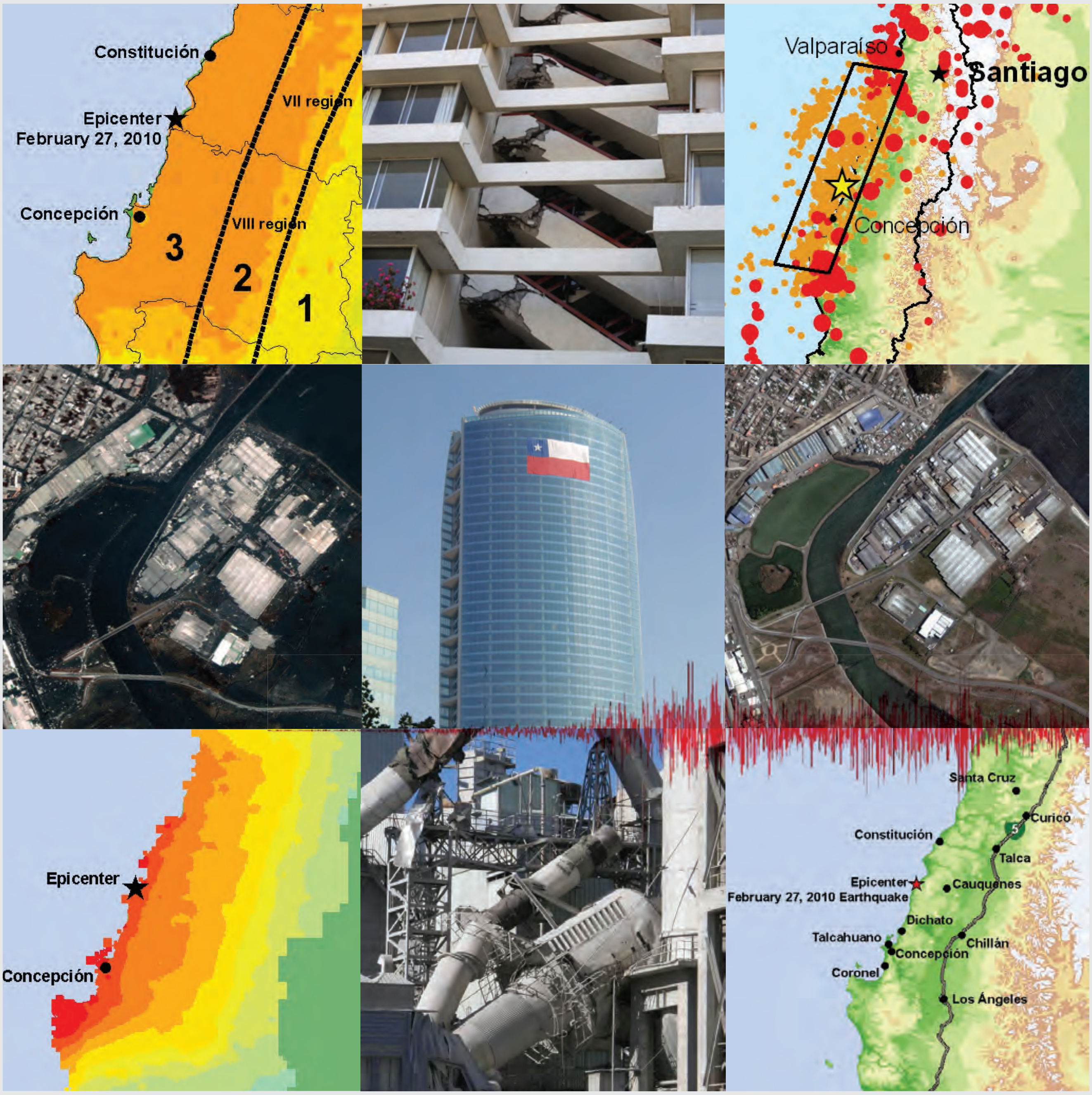
The 2010 Maule, Chile Earthquake: Lessons and Future Challenges



RMS

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INTRODUCTION

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On Saturday, February 27, 2010, at 3:34 a.m. local time, a powerful earthquake struck offshore of the Maule region in central Chile. Occurring along the interface between the Nazca and South American plates, the subduction zone event caused severe ground shaking across a 660 km (400 mi) swath of the country—from Valparaíso to south of Concepción—and generated a tsunami that ravaged the coastline. In all, over 520 people lost their lives in the event. Based on the historical record and significant strain accumulation on the subduction zone, the location and magnitude of the earthquake was not unexpected. The earthquake filled in a "seismic gap" along the subduction zone that had not experienced an event since 1835. In 2011, according to the U.S. Geological Survey (USGS), if one considers worldwide events since 1900, this earthquake's moment magnitude of 8.8 is tied for the sixth largest event in the historical record.

In March 2010, Risk Management Solutions (RMS) deployed two reconnaissance teams to the region to investigate the impacts from the earthquake and tsunami. These teams spent two weeks in the field, collaborating with engineers and seismologists from other organizations, including the University of Chile, the USGS, and Stanford University. Post-event field reconnaissance, in its ability to rapidly and precisely make observations about the impacts from a disaster, is critical in the management of emergency response activities in the short term and the understanding of natural hazards in the long term.

The primary goals of the reconnaissance teams were to confirm ground shaking and tsunami height estimates, as well as to collect empirical data on physical damage to the property and infrastructure within the impacted region. With the extent of damage and rising insurance industry losses, RMS re-deployed a team in May 2010 and then again in December 2010. From this extensive reconnaissance work, in conjunction with modeling efforts, RMS confirmed its initial insured loss estimate of $7 to $12 billion. Chile is a major insurance market, and the devastating event ranks as one of the largest insured catastrophe losses outside of the United States.

The findings presented in this report highlight the unique lessons learned from the 2010 earthquake. The relatively low casualty count and degree of destruction from this event, considering its massive magnitude, demonstrates the success of the Chilean seismic building code in providing superior performance against earthquake ground motions. The geographical concentration of industrial risks, which are highly interdependent upon one another, illustrates how business interruption loss is compounded over time. The status of reconstruction efforts over a year later—particularly along tsunami-impacted coastlines—highlights the complexities inherent to societal recovery after a catastrophe.

The 2010 Maule, Chile Earthquake serves as a stark reminder of the earthquake and tsunami risk to those living along subduction zones—in South America, Japan, North America, and other at-risk regions worldwide. The lessons learned, as well as the additional data continuing to emerge from this event, will ultimately improve the management of earthquake risk for years to come.

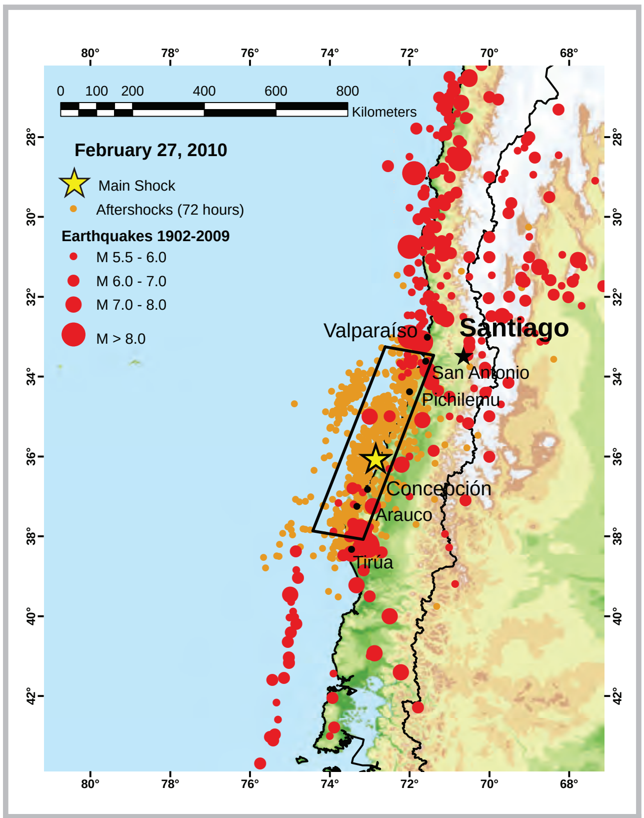
1 THE 2010 MAULE, CHILE EARTHQUAKE

1.1 Seismological Features

The 2010 Maule, Chile Earthquake that struck offshore of Chile during the early morning hours of February 27, 2010, was a subduction zone interface event occurring along the boundary between the Nazca and South American tectonic plates. Along the western coast of South America, the oceanic Nazca Plate plunges, or subducts, beneath the South American Plate at a rate of about 70 mm/yr (2.8 in/year). This type of tectonic environment is referred to as a subduction zone and the interface region between the two plates at depth produces the world's largest earthquakes, including the 1960 M9.5 Chile Earthquake, the 1964 M9.2 Alaska Earthquake, and the 2004 M9.1 Indian Ocean Earthquake.

The size of this event was determined to be moment magnitude (M) 8.8 by numerous seismological agencies, including the Servicio Sismológico of the Department of Geophysics at the University of Chile, and the U.S. Geological Survey (USGS). The earthquake initiated at a depth of 35 km (21.7 mi) and ruptured along the interface between the Nazca and South American plates for almost 450 km (280 mi), from the town of Pichilemu in the north to the Arauco Peninsula in the south. Interpretations of the ground motions indicate that the highest slip was concentrated along a 300 km (190 mi) section of interface and that the zone ruptured to a depth of almost 50 km (30 mi). With an average slip of 7 m (33 ft) across a fault rupture area of approximately 80,000 km^2, the event released an enormous amount of energy—equivalent to approximately 238 megatons of TNT.

As expected, the mainshock was followed by a sequence of aftershocks, though fewer aftershocks occurred compared to other historical earthquakes of similar size. According to the USGS National Earthquake Information Center (NEIC), over 300 aftershocks of M5.0 or greater occurred through April 26, 2010, of which over 20 were M6.0 or greater. The mainshock also caused sudden displacement of the seafloor, generating a series of tsunami waves that significantly impacted the Chilean coast from San Antonio in the north to Tirúa in the south. While the localized impacts of the tsunami waves were severe for some Chilean coastal communities, the far field impacts were minimal.



Central Chile seismicity map, showing the location of the 2010 Maule, Chile Earthquake's rupture area (black box), epicenter (yellow star), and sequence of aftershocks within the first 72 hours of the main event (orange circles). Historical seismicity (from 1902-2009) of M5.5 events or greater shown in red (Data Source: USGS)

1.2 Ground Shaking

Shortly after the M8.8 earthquake, the USGS issued a ShakeMap for the event (http://earthquake.usgs.gov/earthquakes/shakemap/), with estimates of ground motion. One measure of ground motion portrayed in a ShakeMap is the "instrumental" Modified Mercalli Intensity (MMI). The basic MMI scale is a subjective way to differentiate and compare ground motions based on damage levels for areas impacted by an earthquake. The instrumental MMI converts ground motion values, such as peak ground acceleration and velocity, to equivalent MMI values based on past comparisons of direct damage and measured ground motion. Because the ShakeMap is based on actual ground motion observations and theoretical calculations of ground motion, they are not directly linked to damage observations. Thus, the USGS ShakeMap interpretation of instrumental MMI is an important starting point for understanding the potential impact of an event. In order to understand the actual impact of the event, damage observations are necessary. One of the objectives of the RMS reconnaissance work was to determine damage levels for key cities in order to validate ShakeMap MMI values and interpolated ground motion measures.

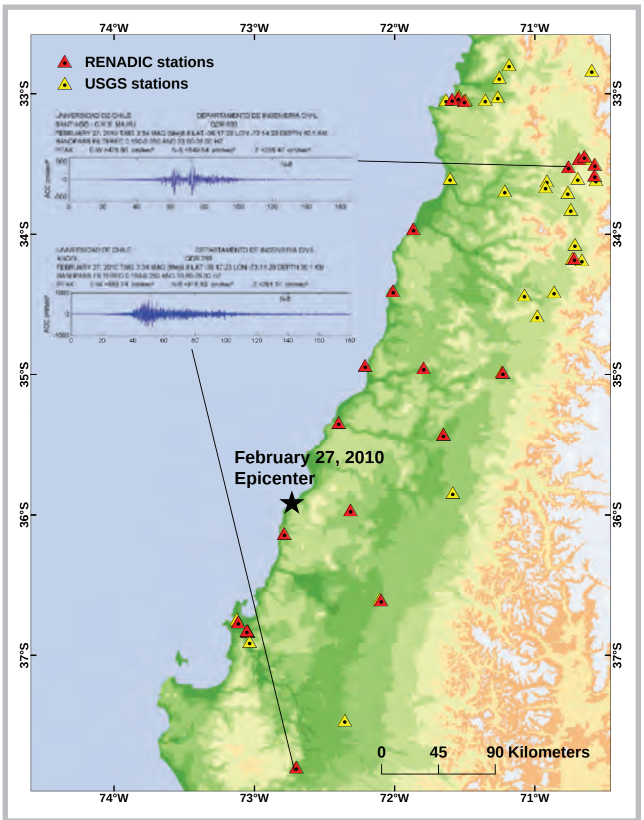
The development of ground motion and intensity maps requires accurate ground motion measurements. The ShakeMap for the 2010 event was produced using ground motion data from approximately 65 USGS recording stations across the Americas, with the closest station 100 km (62 mi) from the earthquake's epicenter. The Chilean national network of accelerometers, known as RENADIC and managed by the Department of Civil Engineering of the University of Chile, had stations closer to the epicenter—at 25 km (15.5 mi). However, the RENADIC network was not utilized for the development of the USGS ShakeMap; overall, the RENADIC network had less than 25 stations within 350 km (217 mi) from the earthquake's epicenter.

In the months following the 2010 event, only a few seismograms were made publicly available by institutions that operate the instruments. For example, the RENADIC network provided horizontal and vertical ground motion recordings for nine stations in the impacted region in early April 2010. Over the past year, more data has become available as it was processed and interpreted. RENADIC released peak acceleration data for 22 stations across Chile in August 2010, with an update in October 2010. With this additional data, the ground motion and intensity footprints can be better constrained. Locations near a seismic recording station have better-constrained ground shaking estimates (provided the local soil conditions at the measurement site are known). In contrast, for locations far from such stations, intensity estimates are calculated using inference techniques and interpolation, resulting in higher uncertainty in ground shaking estimates.

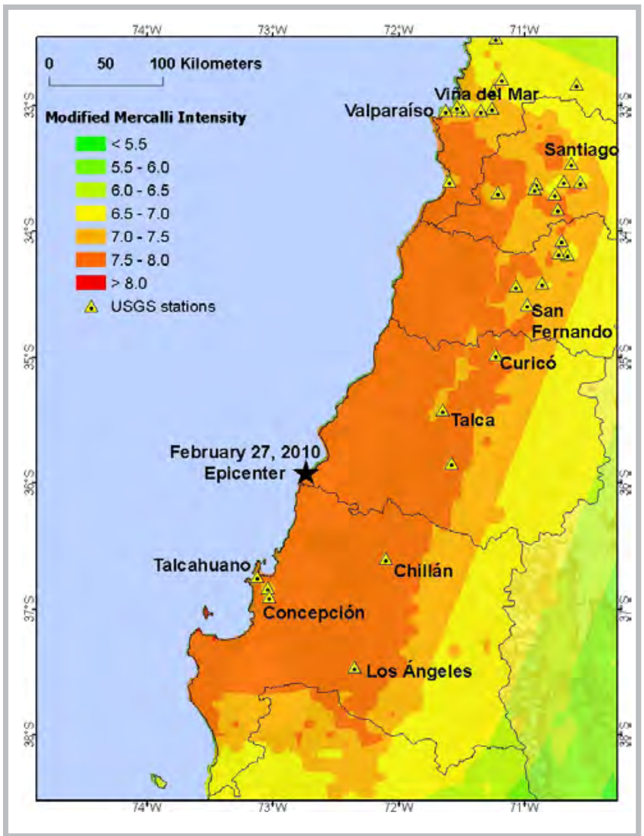
The ground motion footprint for this event included approximately 80% of the 17 million residents of Chile. According to RMS ground reconnaissance, the regions subjected to the most severe ground shaking—and subsequently, the most damage—were Maule and Biobío. Additional significant shaking and damage was observed in O'Higgins and La Araucanía, with

Intensity	Modified Mercalli Intensity (MMI) Description
I	Not felt except by a very few
II	Felt only by a few persons at rest
III	Felt quite noticeably by persons indoors. Many people do not recognize it as an earthquake. Vibrations similar to the passing of a truck. Duration estimated.
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound.
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned.
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Descriptive definitions of Modified Mercall Intensity (MMI) levels I through XII, emphasizing the degree of damage for levels V through IX; MMI level V is where damage begins and MMI level IX is the maximum level observed in the 2010 Maule, Chile Earthquake (Source: USGS)



Seismic network map and topography of the epicentral region, illustrating the locations of the seismic recording stations in the RENADIC network (in red triangles) and the USGS network (in yellow triangles) with respect to the epicenter of 2010 Maule, Chile Earthquake; recordings of horizontal accelerations for two of the RENADIC stations - in Maipú and Angol - are highlighted (Data Source: RENADIC, USGS)



Map of Modified Mercalli Intensity (MMI) estimates, as provided by the USGS ShakeMap program (at 0.5 interval increments), for the 2010 Maule, Chile Earthquake; locations farthest from USGS recording stations (in yellow triangles) are regions where interpolation was needed to estimate intensity values (Data Source: USGS)

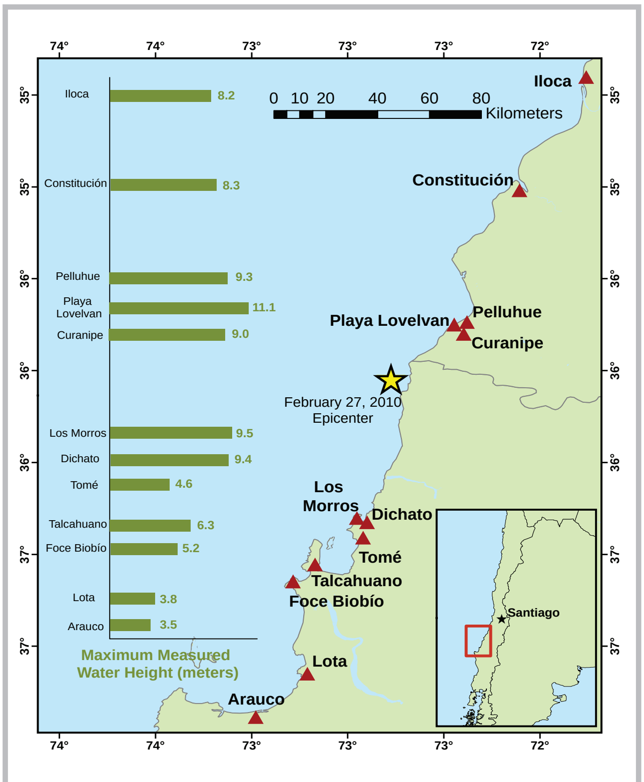
pockets of concentrated damage in Valparaíso and Metropolitan Santiago. The latest data available from RENADIC indicates that the highest ground motions were recorded in Angol, located in the Araucanía Region, which had a maximum acceleration of 0.93 g in the horizontal direction. Significant ground motions were also recorded farther from the epicentral region. In Maipú, located in the metropolitan area of Santiago, a maximum horizontal acceleration of 0.56 g in the north-south direction was recorded by the RENADIC network. This large acceleration is the result of Santiago's location in an alluvial basin, which amplifies ground motion and increases the damage to buildings in the area. In Constitución, which is closer to the event's epicenter, a higher ground motion (0.64 g) was recorded in the horizontal direction.

1.3 Tsunami

Following the 2010 Maule, Chile Earthquake, a Pacific-wide tsunami warning was issued by the Pacific Tsunami Warning Center (PTWC). Fortunately, the far-field impacts along the coastlines of the United States, Japan, New Zealand, and Mexico (among other countries), were minimal and the PTWC eventually cancelled its warning. The PTWC reported tidal gauge measurements of 0.82 m (2.7 ft) in Hanasaki, Japan off the island of Hokkaido and 0.98 m (3.2 ft) in Kahului, Hawaii off the island of Maui. The long travel time of tsunami waves across the Pacific Ocean allowed for the mitigation of the tsunami's impacts. Although some damage was reported to fisheries in Japan, the tsunami waves had the most devastating impact on the local Chilean coastline.

According to eyewitness accounts, the first in a series of tsunami waves hit the local coastline within 30 minutes of the earthquake. The arrival of the first waves coincided with low tide, but the waves that arrived in the subsequent hours rode the incoming tide. In most cases, the second and third waves were described as the main sources of damage. The impact of the tsunami waves varied dramatically along the coastline. Some towns were completely inundated by the waves, and others were barely impacted. In general, the most severely impacted towns were those with north-facing coastline or bay exposure, or those at very low elevations with little or no barriers against the tsunami waves, or both.

The small fishing communities of Dichato and Los Morros, located on the north-facing Coliumo Bay, were particularly devastated as the tsunami waves funneled into the bay. Port facilities at Talcahuano (near Concepción) also face north, and



Tsunami inundation map, with estimates of water heights (in meters) from Iloca to Arauco along the Chilean coastline following the 2010 Maule, Chile Earthquake (Data Source: JRC, 2010)

Tsunami damage in Llo-Lleo, Chile, south of San Antonio, following the 2010 Maule, Chile Earthquake (Source: RMS)

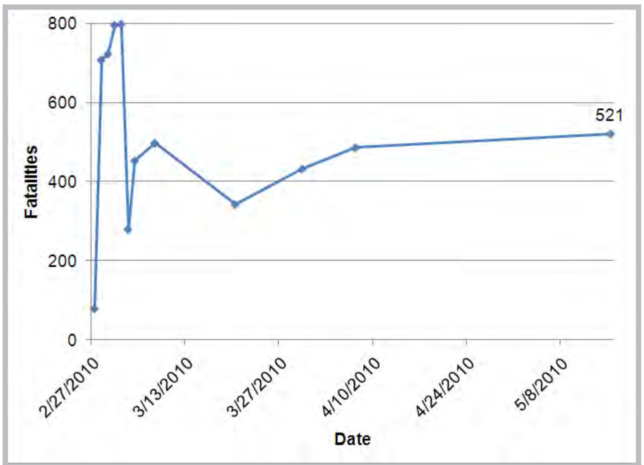
were significantly impacted as well. From the north to south along the tsunami damage zone, Llo-Lleo, Pichilemu, Constitución, Pelluhue, Curanipe, Dichato, Los Morros, Talcahuano, Tubul, Llico, Lebu, and Tirúa—towns at very low elevations with little or no flood protection—experienced the greatest damage. Residential and small commercial structures along the coastline were completely washed away. According to field data collected by the Joint Research Centre (JRC) of the European Commission, waves at Playa Lovelvan, located very close to the epicenter, reached a maximum measured water height of 11.1 m (36.4 ft). Water heights between 8–10 m (26.2–32.8 ft) were recorded at Constitución, Curanipe, Dichato, Iloca, Los Morros, and Pelluhue. According to Chilean government reports, the cities of Constitución, Talcahuano, and Pelluhue sustained the largest number of casualties from tsunami inundation.

Along the western edge of the Arauco Peninsula, the coast was uplifted approximately 1 to 2 m (3 to 6 ft), due to the large displacement on the subduction zone interface at depth. Observed uplift is likely limited to this area because it is the only coastal region directly over significant subsurface rupture. The uplift mitigated the impact of the tsunami waves on communities in this region. Subsidence was observed on a smaller scale (less than 0.5 m or 1.6 ft) along the central coast from Constitución to Bucalemu, but does not pose a significant risk to property; such elevation changes are common in large subduction zone events. In comparison, the 1960 M9.5 Chile Earthquake generated displacements up to 20 m (66 ft). The zone of tectonic subsidence passed through the city of Valdivia, reducing ground elevations by up to 2.5 m (8.2 ft) and causing parts of the city to be abandoned, as streets and houses sank below sea level.

1.4 Casualties

As reported by the Chilean government, there were 524 confirmed dead and 31 missing as a result of the February 27 earthquake. The relatively low death toll in Chile demonstrates the overall efficacy of public awareness, enforced seismic building codes, and quality construction. This is in contrast to the January 12, 2010 Haiti Earthquake, in which hundreds of thousands of people were seriously injured or killed in an earthquake 1/500th the size of the February 27 event. Official casualty estimates from the 2010 Chile event indicate that close to one-quarter of the fatalities resulted from the tsunami following the earthquake (Servicio Médico Legal, 2011). In contrast, RMS research on the 1960 Chile Earthquake indicates that 55% of deaths were attributable to the tsunami waves (see sidebar on *The May 21-22, 1960 Chile Earthquakes*).

As there was no federal protocol for counting casualties, each region used its own approach, leading to difficulties in accurately assessing the number of dead and missing in the week following the event. The counting of missing people and unidentified bodies created added uncertainty, as the double counting of an individual assumed missing but in fact unidentified, had occurred. The counting of fatalities began on February 27 and was reported daily by the National Office of Emergency of the Interior Ministry (ONEMI), through March 5. Concerns and criticism over double counting for casualty estimates ensued, particularly from February 28 to March 3 (when totals reached 700 and climbed to 800). Following this criticism, ONEMI focused on counting only those who could be identified, leading to a reduction in the estimates, with the most recent and final estimate of 524 fatalities and 31 missing as of late 2011.



Number of fatalities as a result of the 2010 Maule, Chile Earthquake, as issued by the Chilean government starting on February 27, 2010 and continuing through May 15, 2010; the final fatality estimate stands at 524 (Source: ONEMI)

The earthquake struck in the early morning hours when most Chileans were asleep. The time of day when the earthquake occurred, coupled with robust building codes and seismically-resistant residential construction, played a crucial role in preventing a larger number of casualties due to ground shaking. Historically, the primary cause of earthquake fatalities is the collapse of poorly constructed or non-seismically resistant buildings (e.g., adobe structures). In the 2003 Bam, Iran Earthquake, for example, much of the mud brick and adobe construction (which constituted 90% of the residential structures in the city) collapsed in the earthquake. Occurring in the early morning hours, when the population was asleep, the earthquake caused approximately 31,000 people to perish. Similarly, the death toll in the city of Chillán following the 1939 earthquake reached approximately 30,000 residents, killed by the collapse of unreinforced masonry residential structures.

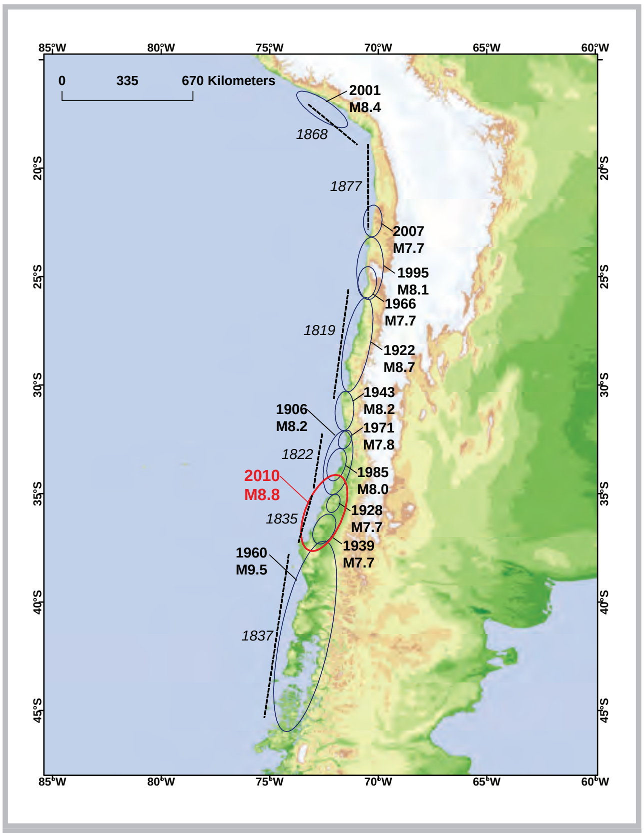
Despite the lack of official warning, both historical experience and proactive outreach in Chile have made coastline communities aware of the potential for an earthquake-induced tsunami. For example, just two weeks prior to the earthquake, local firefighters in Constitución had carried out an earthquake drill, instructing the coastal population to move to higher ground in the event of a severe earthquake. Similarly, in Talcahuano, the community appeared well-prepared to respond to tsunami warnings. Within minutes of a M6.9 aftershock that struck central Chile on March 11, 2010, most of the residents and workers in the vicinity of the Bío Bío cement plant, where the RMS reconnaissance team was located, were en route to higher ground. Soldiers directed traffic at major intersections; automobile and pedestrian traffic was generally orderly. The society's response to the aftershock suggests that future losses can be mitigated if the current level of risk awareness is sustained.

Rendering by John Clements Wickham of the destruction of Concepción following the February 20, 1835 earthquake (in Robert Fitzroy's Narrative of the Surveying Voyages of His Majesty's Ships Adventure and Beagle)

Residents of Talcahuano moving to higher ground following a M6.9 aftershock on March 11, 2010 (Source: RMS)

1.5 Historical Perspective

The last large event to occur on the segment of the subduction zone ruptured in the 2010 event was an estimated M8.5 earthquake in 1835. The damage from this earthquake was observed by Charles Darwin, who noted that in Concepción "it is absolutely true there is not one house left habitable." With a convergence rate of almost 70 mm/yr (2.8 in/year) along the subduction zone, this segment of the zone accumulated a slip deficit of 12 m (40 ft) in the 175 years since the 1835



Historical earthquake events of M7.7 and greater along the western coastline of Chile, highlighting the February 27, 2010 M8.8 event (in red); event information based on the RMS® Chile Earthquake Model, with rupture lengths of events occurring before 1900 shown as black lines, and magnitudes and approximate rupture areas of events occurring since 1900 shown as blue ellipses event—a buildup of strain capable of producing a M8.0 event or greater.

For this reason, the 2010 event was not unexpected, as it filled a known "seismic gap" (Ruegg et al., 2009) along the subduction zone interface. The 2010 rupture is bounded to the south by the 1960 rupture zone and to the north by the 1906 and 1985 rupture zones. The 1906 M8.2 earthquake caused considerable damage in Valparaíso, due to both ground shaking and fires following the event, and impacted a wider region that included Viña del Mar and Santiago. The region of strong shaking in the 1906 event is believed to extend from Vallenar to south of Santiago. The 1985 M8.0 earthquake was felt from Valdivia to Copiapó, causing extensive damage to central Chile and impacting the cities of Valparaíso, Viña del Mar, Santiago, and Rancagua. The 1985 event also generated damaging tsunami waves with wave heights of 1.1 m (3.6 ft) in Valparaíso, 1.8 m (5.9 ft) in Talcahuano and 2 to 3 m (6.6 to 9.8 ft) in San Antonio. Waves propagated across the Pacific Ocean, reaching Hawaii with heights of less than 1 meter (3.3 ft).

The 1960 M9.5 event remains the largest earthquake observed globally since 1900, with the most severe ground shaking damage occurring in the Puerto Montt-Valdivia region of Chile. The 1960 event also generated a series of tsunami waves that impacted the Chilean coast from Lebu to Puerto Aisén, and reverberated across the Pacific Ocean, causing fatalities in Hawaii, Japan, and the Philippines. According to the USGS, a maximum run-up height of 10.7 m (35 ft) was observed in Hilo, Hawaii. ■

The May 21–22, 1960 Chile Earthquakes

The energy released in the M9.5 earthquake of May 22, 1960 at 3:11 p.m. local time was equivalent to 2.67 gigatons of TNT; this energy release remains the greatest ever recorded in the annals of seismic observations. Adding to the destruction, the mainshock was preceded by a series of shocks that began at 6:02 a.m. local time on Saturday, May 21, 1960, with a M7.9 event on the Arauco Peninsula of Chile, causing casualties and property damage in Concepción.

Due to the proximity in time and space of these two events, significant uncertainty exists about the individual effects of these earthquakes, especially in the number, geographic location, and cause of human casualties. Moreover, there remains confusion as to the fatalities caused by the M9.5 event itself. For example, NOAA estimates between 490 and 5,700 fatalities from the M9.5 earthquake and basin-wide tsunami. In contrast, the USGS estimates that 1,655 were killed in the event.

Utilizing the official number of casualties reported by Rothé (1969), which asserts that approximately 1,380 individuals were victims of these two events (660 fatalities and 720 declared missing and assumed to have perished in the tsunami waves or a landslide), RMS conducted an analysis to ascertain the actual fatality figures from these two earthquakes—both within Chile and across the affected coastlines of the Pacific Ocean.

It was established with reasonable confidence that approximately 190 of the deaths occurred on May 21, with the remaining 1,190 on May 22. As a result, the M9.5 earthquake was responsible for close to 90% of the fatalities (Pomonis, 2010). Moreover, RMS estimates that 760 individuals were killed by tsunami waves, 370 perished in landslides (with 300 in one landslide alone), and the remaining 250 deaths were due to other ground shaking-related causes, including building collapse, falling debris, and fire following the earthquake. ■

Damage to wood frame dwellings in Valdivia, Chile, following the May 22, 1960 Chile Earthquake (Source: National Aeronautics and Space Administration)

2 DESIGN AND CONSTRUCTION IN CHILE

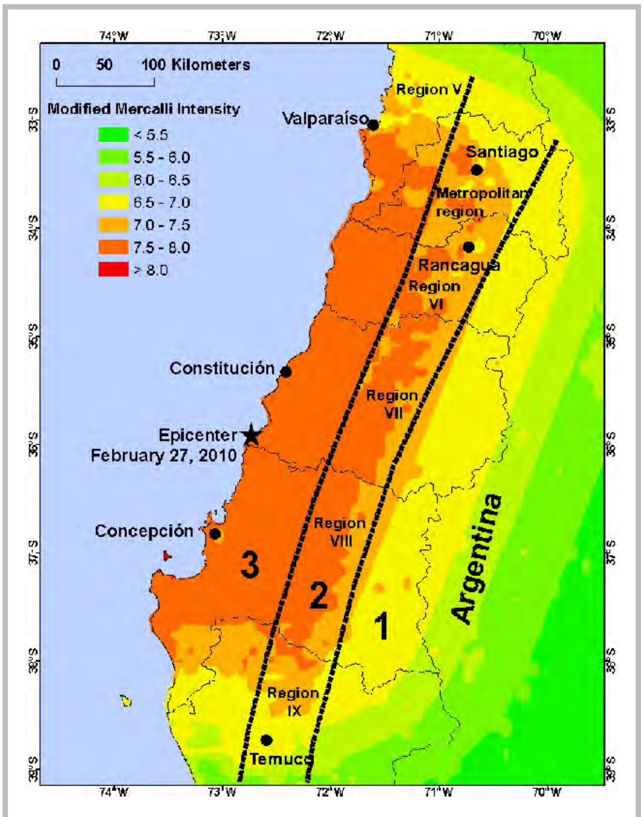
Through reconnaissance efforts, RMS confirmed that structural performance in the 2010 Maule, Chile Earthquake was a function of good design and construction practices—the result of the country's experience with frequent strong earthquakes. Similar to other high-risk regions around the world, such as Japan and the U.S., with each damaging earthquake throughout the 20th century, updates to seismic design provisions in the national building code were implemented.

2.1 History of the Chilean Building Code

While there were higher magnitude events earlier in the 20th century—such as the 1906 Valparaíso and 1922 Vallenar earthquakes—the Chilean building code owes its origins to the December 1, 1928 Talca Earthquake. The city of Talca was severely impacted by this earthquake, with historical reports of collapsed unreinforced masonry buildings, railway and telephone line damage, and a tsunami destroying the local coastline near Constitución. As a result of the damage, the Chilean government passed a law in 1929 establishing a committee tasked with developing building code provisions (Paz, 1995).

In 1935, Chile's first national building code containing these provisions, the Ordenanza General de Construcciones y Urbanizaciones (General Law and Ordinance on Construction and Urbanization), was enacted. The code established rules regarding urban planning, as well as design allowances for various classes of buildings. For example, the practice of confined masonry construction, which began following the 1928 Talca event, was officially prescribed in this code. Then, the 1939 Chillán Earthquake, which destroyed most of the city of Chillán and caused approximately 30,000 deaths, led to a review of the code. An immediate update to the provisions included limitations on heights for various construction materials (e.g., reinforced concrete, steel, timber, masonry, and adobe), as well the prohibition of unreinforced masonry construction and strict provisions for adobe construction. However, given the increased costs associated with these provisions, amendments were made and officially published in 1949, eliminating height limitations for steel and reinforced concrete structures and allowing confined masonry structures up to four stories in height (Wood et al., 1987).

More than two decades elapsed before the next major revision of Chile's building code. The



Seismic zonation of the regions (V, VI, VII, VIII, IX, and Metropolitan region) impacted by the 2010 Maule, Chile Earthquake, as established by the latest Chilean seismic design provisions (NCh 433-1996), overlaid on the intensity map of the 2010 event

INDITECNOR or Instituto Nacional de Investigaciones Technógicas y Normalización, a government organization tasked with reviewing the Ordenanza after major earthquake events, was in the process of making recommendations for updates to the code when the 1960 Chile (Valdivia) Earthquake struck in May. Now known as the Instituto Nacional de Normalización (INN), the INDITECNOR completed its recommended updates to the code, with approval of the Cálculo Antisísmico de Edificios (Earthquake Resistant Design of Buildings) in 1972. While the 1949 Ordenanza, with minor modifications, is still in force today, the sections of the code governing seismic design provisions was replaced by these 1972 provisions (NCh 433-1972).

The INN published a second version of its seismic code in 1985, and a third update in 1989. The 1989 seismic design code reflected the initial lessons learned from the 1985 Llolleo Earthquake, which struck central Chile on March 3, 1985. Chile's seismic design provisions were revised again in 1993 (NCh 433-1993) and 1996 (NCh 433-1996), with NCh 433-1996 being the code currently used in Chile. While NCh 433-1996 is the main seismic design code for building construction in Chile, there are other complementary design codes that apply to specific structures and materials, such as industrial facilities (NCh 2369-2003), base-isolated structures (NCh 2745-2003), confined masonry structures (NCh 2123-1997), and many more. In particular, the seismic code for industrial facilities includes recommendations and design rules for mechanical equipment aimed at minimizing service or production interruptions.

The NCh 433-1996 building code divides the country into three seismic zones based on seismic hazard. Cities near the coast (i.e., along the subduction zone), such as Concepción, Valparaíso, Viña del Mar, and Constitución, have the most stringent design requirements (Zone 3). Talca and Chillán, which were heavily affected by the 2010 Maule, Chile Earthquake, are also in Zone 3. Santiago, Rancagua, Curicó, and other inland cities are classified with intermediate hazard (Zone 2). Zone 1 includes regions along the eastern edge of the country with the lowest hazard, such as the city of Pucón.

Similar to the U.S. seismic design provisions, the Chilean seismic design code classifies buildings according to their occupancy importance (e.g., essential facilities versus buildings for general use) and structural characteristics (e.g., material, height, lateral load resisting system), and defines requirements and recommendations for static and dynamic analysis. For

Tall reinforced concrete shear wall building in the comuna of Las Condes in Metropolitan Santiago, Chile, a typical apartment building in region impacted by the 2010 Maule, Chile Earthquake (Source: RMS)

Central business district of Santiago, Chile, illustrating the density of the building stock and including the Torre Titanium La Portada (in the center background) (Source: RMS)

example, in the calculation of earthquake lateral loads (which a building must resist), a building importance factor ("I" factor), a response modification factor ("R" factor) for energy dissipation, and a "C" coefficient based on the structural period of vibration and soil conditions are all utilized.

2.2 Construction Patterns

Two important concepts in earthquake resistant design are lateral resistance and ductility. Lateral resistance refers to the horizontal bearing capacity which is capable of developing in a structure before it collapses. The ductility is the absorption and dissipation of energy within a structure before collapse. The Chilean approach to earthquake resistant design has traditionally been high strength and low or moderate ductility (i.e., strong, stiff structures).

As a result, the majority of buildings in Chile are constructed with masonry (confined or reinforced) or reinforced concrete. A small percentage of high-rise commercial buildings in major cities, such as Santiago, are constructed using steel framing, and a small percentage of low-rise residential buildings are constructed of adobe or timber. Unreinforced masonry (URM) buildings, prohibited from being built since the 1939 Chillán Earthquake, comprise a small subset of the exposure at risk in Chile.

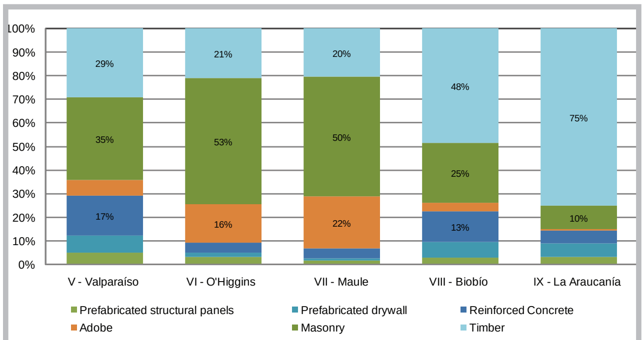
2.2.1 Reinforced Concrete Construction

In Chile, the majority of high-rise commercial and multi-family residential buildings in urban areas are reinforced concrete structures with shear walls. Chile has experienced several severe earthquakes in the past 100 years, and Chilean structural engineers and builders have used these experiences to inform the type of structural systems to utilize. Since the establishment of the Chilean building code, Chilean engineers have designed and built very stiff structures, configured with a density of shear walls to withstand lateral loads. The large wall densities of these buildings (defined as the ratio of the wall area in each principal direction to the floor plan area [Moroni, 2002]) limits lateral movement of the structure (e.g., measured by inter-story drift).

Reinforced concrete shear wall structures have performed well in past earthquakes in Chile, including the 1985 Santiago Earthquake. Based on the current seismic code in Chile, reinforced concrete shear wall structures must resist a base shear of 5–6.7% and the inter-story drift must be less than or equal to 0.002 (Moroni, 2002). This seismic requirement leads to relatively stiffer reinforced concrete shear wall buildings as compared to the more flexible buildings in the United States. In Chile, reinforced concrete shear wall buildings commonly have a wall density greater than 1.5% (2.8% on average), compared to a wall density of 0.5% in the U.S. (Moroni and Gomez, 2002). However, the recent surge in the construction of taller buildings and commercial properties with more open office spaces may begin to challenge the Chilean tradition of building very stiff reinforced concrete shear wall structures with large wall densities (Moroni and Guzman, 1998).

2.2.2 Confined Masonry Construction

Confined masonry is the most prevalent construction type used for single-family residential structures, as well as low and mid-rise apartment buildings. Similar to reinforced concrete construction, stiff structures with large wall densities of 2–4% are common for residential confined masonry construction. These masonry structures consist of load-bearing unreinforced masonry walls "confined" with cast-in-place reinforced concrete tie-columns. The tie-columns are connected with reinforced concrete tie-beams, which are cast



Residential construction patterns by region, highlighting the use of confined masonry in O'Higgins and Maule and the use of timber in Biobío and La Araucanía (Data Source: INE, 2003)

Confined masonry building in Coelemu, Chile (Source: RMS)

after the construction of masonry walls. Although confined masonry walls have limited shear strength and ductility compared to reinforced concrete walls, buildings of this type have behaved satisfactorily in past earthquakes.

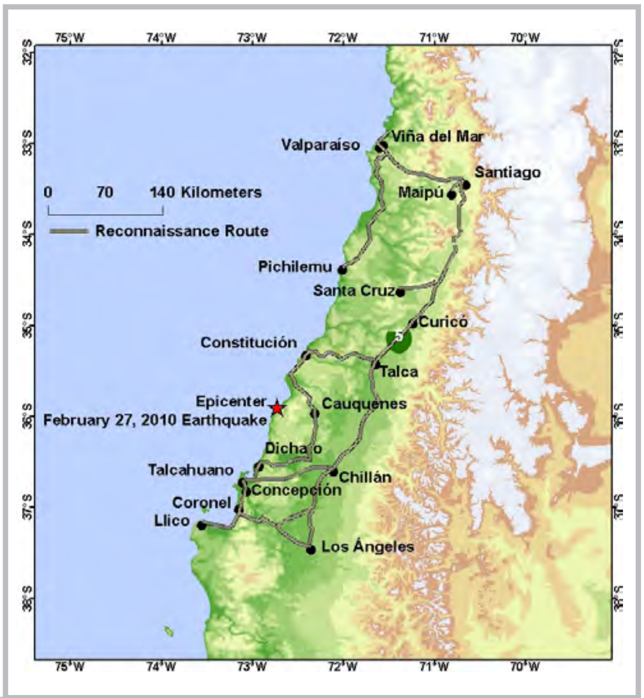
2.2.3 Regional Variation in Construction

The performance of modern structures in Chilean earthquakes testifies to the adequate seismic design requirements of the building code, the government's ability to enforce the code, and the public's willingness to follow principles of earthquake-resistant building design. However, the structures in some regions of Chile performed significantly better than others, partly due to the regional variation in construction. Data from the 2002 Chilean housing census indicate that approximately 50% of the residential structures in two of the impacted regions—O'Higgins and Maule—are constructed of confined masonry, while timber and adobe materials each make up about 20% of the residential structures in these two regions. Farther south, in the Biobío and La Araucanía regions, timber construction overtakes confined masonry as the most common material used to build residential structures.

A building's construction material is highly correlated to the damage it is expected to sustain in an earthquake; RMS reconnaissance teams observed this correlation throughout the impacted area. It should be noted that while regional variation in construction practices influenced the damage patterns, the ground shaking intensity also exhibited high regional variation and played a major role in the resulting damage. For example, in Valparaíso, horizontal ground motions generally ranged from 0.1 to 0.4 g; in contrast, horizontal ground motion recordings in Maule ranged from 0.4 to 0.6 g. ■

3 GROUND RECONNAISSANCE

In March 2010, RMS reconnaissance teams spent two weeks in Chile, investigating the impacts of the 2010 Maule, Chile Earthquake. Several team members returned in mid-May to spend additional time investigating the tsunami damage along the coastline, as well as changes in coastline elevations. And in December 2010, a final visit was made to investigate the reconstruction progress, particularly of large industrial facilities that had been studied on the previous trips. Beginning in the Santiago metropolitan area, the teams' reconnaissance routes spanned from Concón (just north of Viña del Mar) in the north to Los Ángeles in the south.



Route of RMS reconnaissance teams in central Chile during March 2010, highlighting key cities along the route in both the capital and epicentral regions

3.1 Damage Trends

Metropolitan Santiago, with a population of 7.2 million, experienced brief disruptions to electricity and communications, as well as collapsed bridges and roadways. The Santiago International Airport was closed for several days following the event. Coastal towns closer to the epicenter, including Constitución and Dichato, were overwhelmed by tsunami waves; other towns were unreachable due to roadway or bridge damage. Ports in the region sustained damage and were closed for inspections, including those in Talcahuano and Coronel.

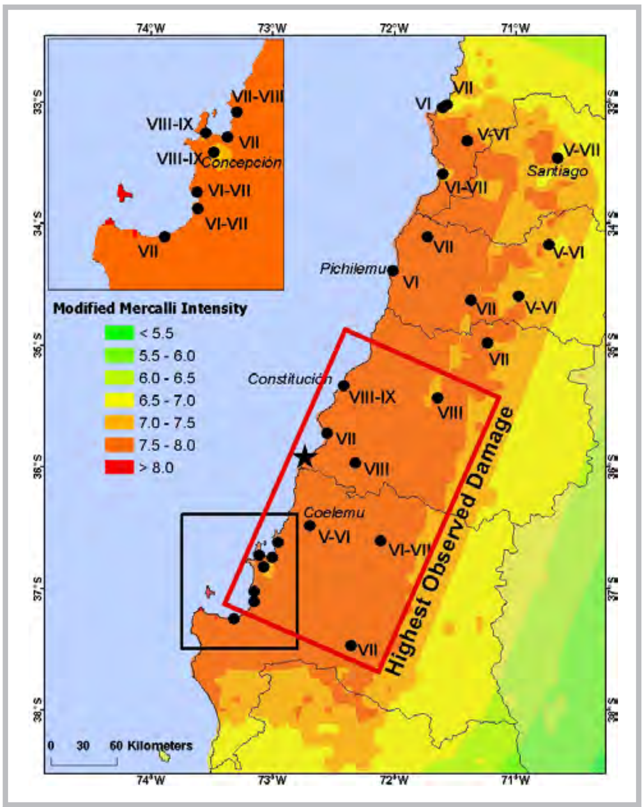
Beyond the observed tsunami-inundated ports, airport closures, highway failures, and bridge collapses, a high concentration of damage was sustained in Concepción. Within this second largest city in Chile and capital of the Biobío region, looting was reported and a curfew was in place for days following the earthquake. When the RMS reconnaissance team visited Concepción on March 10, 2010, life was still far from normal. Many retail stores were closed and military personnel patrolled the streets. In other inland towns along the reconnaissance route, including Talca and Chillán, significant building damage was observed. A higher percentage of building collapse was observed in areas with more adobe structures. For example, in Talca, a relatively large percentage of homes constructed using adobe sustained heavy losses. In comparison, noticeably better structural performance was observed in Chillán because the 1939 Chillán Earthquake had destroyed most of the adobe and unreinforced masonry structures in the area.

Damage to roadway near Lota, Chile following the 2010 Maule, Chile Earthquake (Source: RMS)

The Chilean wine industry, in towns such as Santa Cruz, lost significant amounts of revenue, as many liters of wine were lost and tours were suspended throughout the region. Damage to heavy industrial facilities, particularly in Talcahuano, resulted in prolonged production interruptions. With approximately 370,000 impacted households and thousands of schools in need of repairs, the reconstruction efforts have begun and will continue for years to come.

3.2 Ground Shaking Intensities

RMS compared its damage observations with the initial estimates of Modified Mercalli Intensities (MMI) provided by the USGS ShakeMap program. The



The MMI contours as estimated by the USGS immediately following the 2010 earthquake as compared to the RMS reconnaissance team observations (i.e., MMI levels noted next to locations denoted as block dots); the region of highest observed damage is highlighted (in red box)

USGS ShakeMap intensities were estimated at VII or higher for a large swath of central Chile—from Santiago to south of Los Ángeles and the region of La Araucanía. The RMS reconnaissance teams visited all of the major population and exposure concentrations across this region, as well as numerous smaller communities, with the objective of determining MMI values based on the observed damage. For these assessments, the RMS team examined a range of structures with varying construction, occupancy, height and age. In some of the smaller communities, this was more difficult due to the limited variation of structures present.

The RMS-estimated intensity levels by city differed from the ShakeMap estimates, primarily because the USGS estimates were interpolated from ground motion measurements and were not directly linked to ground shaking observations. While extensive tsunami damage was observed in many coastal communities, it is important to note that the MMI values are based solely on observed shaking damage.

Across Santiago, RMS estimated intensities ranging from MMI V to VII; many modern high-rise buildings in the central business district sustained no visible structural damage and re-opened for business within a few days of the event. In general, the regions of Santiago with the highest MMI values were underlain with poor soils that amplified the ground motion. The industrialized coastal region south of the epicenter (e.g., Talcahuano) was one of the hardest hit regions, sustaining both tsunami damage and ground shaking levels between VIII and IX. In Concepción, the MMI levels from the USGS ShakeMap program were estimated between VII and VIII. From ground reconnaissance, RMS estimates that MMI levels were higher in this region—measuring as high as IX in some parts of the city.

Through ground reconnaissance efforts, RMS concluded that the region of highest damage corresponded to a zone centered on the coast near the event's epicenter and extending inland to include the major cities along Chile Highway 5 (Ruta 5). The northern boundary of this zone spans from the inland town of Talca to Constitución along the coast. The southern boundary spans from Coronel and Lota along the coast to Los Ángeles in the central valley. This high damage region lies above a zone of high slip on the subduction interface (inferred from ground motion inversions).

3.3 Key Observations

Damage across a wide range of property exposure—commercial, industrial, residential, and public and industrial facilities—is discussed in the following sections. The key observations across the impacted region included:

- An overall acceptable performance of building structural systems;
- Significant damage to nonstructural building elements and contents;
- Significant business interruption (BI) losses to commercial and industrial facilities; and
- A better relative performance of confined masonry structures, as compared to light metal structures.

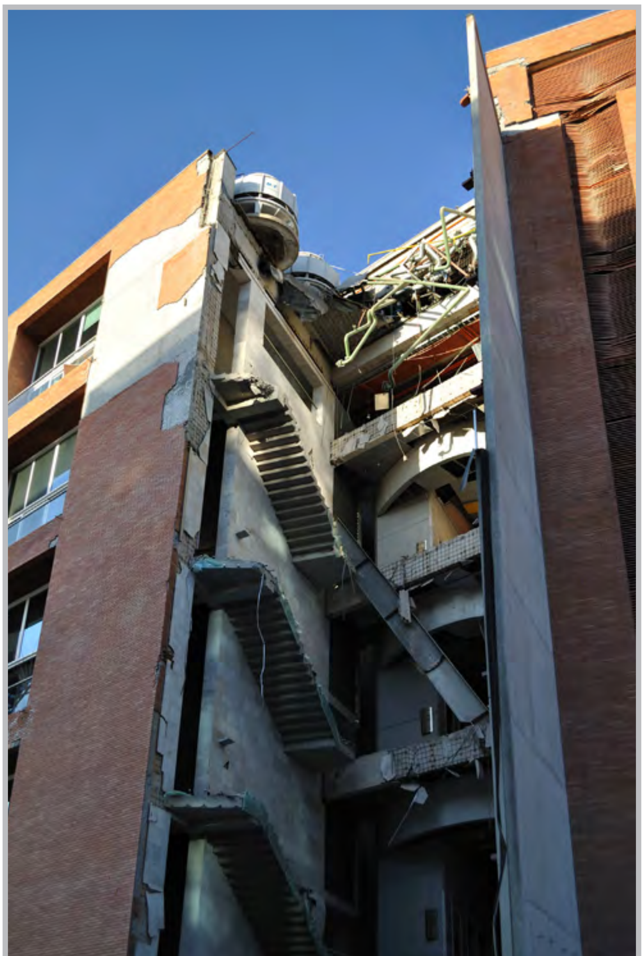
Overall, the event in Chile did not fundamentally change the earthquake engineering community's understanding of the performance of structures; the high seismic design standards of Chilean construction were evident across the modern building stock. However, areas for continued investigation include the collapse of tall reinforced concrete buildings in Concepción and the failure of bridges throughout the epicentral region. The occurrence of the 2010 earthquake, affecting an area with many well-engineered structures, presents immense learning opportunities for the structural engineering community. Principles of earthquake-resistant design can be validated by studying both well-designed buildings and heavily damaged ones. ■

4 COMMERCIAL PROPERTY DAMAGE

Structural, nonstructural, and contents damage to commercial property in the 2010 earthquake was observed across central Chile. Given the variation in building stock characteristics and observed damage patterns, observations are presented for two different regions of Chile—the capital region, which includes Santiago and neighboring cities, and the epicentral region, which includes cities closer to the epicenter of the earthquake, including Concepción.

4.1 Building Damage: Capital Region

The reconnaissance teams' investigation into the capital region concluded that most of the commercial and multi-family residential buildings, built in the mid-1970s or after, and in compliance with the 1972 seismic code, performed reasonably well in the earthquake. The overall building stock experienced slight to moderate damage. In the central business district of Santiago, newer high-rise and other tall buildings, built after the mid-1990s and in compliance with the 1993 or 1996 seismic design codes, sustained minimal damage. Through a survey of the exteriors of these taller structures in the city center, there was no evidence of damage, such as broken windows or missing cladding.



A building in the Huechuraba district of Santiago that sustained heavy damage as a result of ground motion amplification in the basin (Source: RMS)

In Santiago Province, structures in the comunas (communes) of Huechuraba, Las Condes, Macul, Maipú, Santiago, and Quilicura were investigated. In Huechuraba, which is situated in a basin, there was evidence of ground motion amplification. The thick accumulations of sediment in basins can trap seismic energy and amplify it, causing a longer duration of ground shaking. This was particularly true for the high-amplitude, low-frequency ground motions that moved through the basin in the 2010 earthquake. The Huechuraba region contains a small business district, in which approximately one dozen buildings had sustained heavy damage. While none of the buildings had collapsed, some of the buildings had serious cladding issues, and others had failed columns and shear walls, suggesting that they would at least require significant structural repairs. The Radisson Hotel sustained significant damage, with failed columns, infill walls, cladding, and no water or electricity. The poor performance of these modern structures emphasizes the critical importance of basin effects, as well as proper design and construction techniques.

Soft story failure of a multi-family residential building in Maipú, Chile (Source: RMS)

Reports from the University of Chile indicated that the ground shaking was particularly strong in the Maipú region. The RMS team visited an apartment building on Avenida Tristan Valdez in Maipú that collapsed due to a soft-story failure. Soft-story structures, possessing large ground floor openings, are collapse hazards in strong ground shaking.

In Valparaíso Province, investigations were focused in Valparaíso and Viña del Mar. Exposure in this region is concentrated in Viña del Mar, with a much smaller amount in Valparaíso. Viña del Mar is considered one of the more affluent parts of the country, with a majority of the economy driven by tourism. The port facilities in Valparaíso are the main industry for this city. In Valparaíso, most commercial building damage occurred in tall buildings, which generally relied on reinforced concrete shear walls for lateral resistance. Damage was concentrated in the portion of the city that faces north along the bay, located at the base of the mountains and a few hundred meters from the water. The soil in this area is at the edge of a soft, 80-year old fill, and likely to be where the beach was located before the fill was added.

In Viña del Mar, several groups of buildings sustained serious structural damage. In every case, this occurred in tall reinforced concrete shear wall buildings. Common signs of damage included ruptured shear walls, damaged staircases, insufficient seismic joints, and broken non-structural elements such as partition walls.

Shear wall failure observed in Viña del Mar, Chile, illustrating insufficient confinement and poor detailing of hooks (Source: RMS)

These investigations indicate that the two main contributing factors to structural damage of mid- and high-rise buildings in the capital region were soil amplification, where softer sedimentary soil is concentrated, and inadequate design and quality of construction. There were also several isolated cases where differential ground settlement and soft-story mechanisms had contributed to structural damage. In many cases, a building's shear walls appeared

Damage in a tall apartment building in Viña del Mar, Chile; the shear wall failure was likely a result of poorly-detailed transverse reinforcement and insufficient wall thickness, as the concrete ruptured in compression and its longitudinal bars buckled (Source: RMS)

Collapse of low-rise confined masonry commercial structures in Concepción, Chile (Source: RMS)

to be inadequate due to insufficient thickness, poor confinement at boundary elements, insufficient shear reinforcement, or building configurations that concentrated or amplified loads in particular walls. Cyclic loading and long earthquake duration likely played a significantly role in this event; these phenomena are still the subject of investigation and research. In particular, researchers are investigating the impact of tensile loading of shear walls and its influence on subsequent compression failure.

4.2 Building Damage: Epicentral Region

In the Maule and Biobío regions, RMS teams visited Arauco, Chillán, Concepción, Constitución, Los Ángeles, Penco, and Talcahuano. The main construction class for high-rise and tall commercial buildings in Concepción is reinforced concrete, and the damage to these properties ranged from minor damage to full collapse. Where structural damage was observed in Concepción, the reason for each structure's poor performance was not always immediately evident. Cases involving unreinforced masonry were straightforward, but modern reinforced concrete high-rise buildings also failed. While detailed investigations are needed to determine the reason for structural failures, some causes could be: shear failure in structural elements due to insufficient shear reinforcement; localized failure in coupling beams due to improper reinforcement detailing; overstressed structural elements at discontinuities in the structure's stiffness or load path; damage at seismic joints; and localized ground failure and differential settlements. The prevalence of these well-studied failure modes suggests that the engineering community can prevent this type of damage in the future.

Low-rise commercial structures in Concepción's city center primarily consist of two- to three-story structures built in the 1940s and 1950s. These buildings house small- to medium-sized retail shops, markets, and bazaars, as well as small hotels, and are primarily unreinforced masonry buildings or confined masonry buildings with wood or metal truss

Damage to commercial buildings in Concepción, Chile (Source: RMS) roofs. Structural failure to these older low- and mid-rise commercial buildings was due to lack of confinement and insufficient longitudinal rebars in the reinforced masonry buildings, as well as poor quality of construction. The majority of the heavily-damaged buildings were not in compliance with the existing seismic building code.

4.3 Nonstructural and Contents Damage

One of the key drivers of loss during the 2010 Chile earthquake was damage corresponding to the nonstructural elements of the building. Damage to nonstructural elements such as partition walls, suspended ceilings, doors, and windows, as well as contents, was widely observed both in the capital and epicentral regions. From an earthquake engineering perspective, damage to nonstructural elements is not only triggered by the level of displacement imposed on the building, but also the level of the floor acceleration imposed on it. In particular, the losses corresponding to the building contents are primarily a function of the level of the floor acceleration experienced during the earthquake. RMS reconnaissance teams verified that contents damage to buildings in cities located far from the epicenter (such as the capital region) was generally concentrated in upper floors of multi-story buildings compared to the lower floors—primarily due to the higher levels of floor acceleration on upper floors.

Furthermore, there were numerous examples in which a building's structural damage was minimal, but the building contents were destroyed. In these cases, the structural performance of the building was superior or the level of inter-story drift in the building did not trigger structural damage. However, contents were damaged due to very high floor accelerations or improper anchorage.

The observed damage to commercial nonstructural

Overturning of a water tank on the top floor of an apartment building in Viña del Mar, Chile (Source: RMS)

Contents damage to two-story lighting store in Renca, Chile (Source: RMS)

elements and contents in both the capital and epicentral regions ranged from minor to severe. In the capital region, commercial contents losses were generally limited. Some notable exceptions included a retail lighting store in the Renca district of Santiago with approximately 100 tons of broken glass, as well as tall buildings in the Huechuraba district suffering damage to their mechanical and electrical equipment, such as overturned water and gas tanks at the upper floors due to improper anchorage. Commercial properties along the coastal region in Viña del Mar (with underlying soft soils) suffered significant contents losses as well.

Contents losses were more extensive in the epicentral region, particularly for businesses with sensitive inventory, such as retail supermarkets and electronics stores, or businesses impacted by tsunami waves. Dozens of hotels were non-operational in the weeks following the event due to nonstructural damage to elevators and partition walls. Looting contributed to contents losses in a few isolated cases as well. In the tsunami-affected areas of Talcahuano and Constitución, many commercial businesses sustained total contents losses in their lower floors. ■

Partial collapse of O'Higgins Tower in Concepción, Chile (Source: RMS)

Torre O'Higgins

The 2010 Maule, Chile Earthquake caused the partial collapse of the O'Higgins Tower (Torre O'Higgins) in Concepción. This 21-story reinforced concrete structure experienced localized losses of vertical carrying capacity as a result of the earthquake's ground motion. With construction completed in 2008, this office building was designed to the latest Chilean seismic code and its failure was not anticipated, given the construction standards. The building experienced dramatic failures in several of its upper levels that were likely a result of stiffness discontinuities and vertical irregularities in the structure.


O'Higgins Tower before the 2010 Maule, Chile Earthquake (Source: http://img140.imageshack.us/i/concecentro038.jpg)

As seen in the photograph above, the most severe damage occurred at setbacks in the floor plan. The north and west faces of the building showed few signs of damage and appeared more stiff and regular in geometry than the other faces, so the localized failures on the south and east faces were most likely due to the horizontal and vertical irregularities of the structure (e.g., irregular torsional stiffness). While it has not been confirmed, the Director of Works of Concepción had reported in April 2010 that some modifications to the building's design might have led to its collapse. Because the earthquake occurred very early in the morning, this building was unoccupied at the time of the event. According to the local municipality, the O'Higgins Tower is one of nine buildings scheduled for demolition due to the extreme hazard that it poses to public safety. Moreover, the demolition of O'Higgins Tower takes precedence over other buildings due to its location in the heart of Concepción. In August 2011, the safe demolition of the tower has begun and is expected to be complete by the end of the year. ■

Overturned Alto Río building in Concepción, Chile (Source: RMS)

Edificio Alto Río

The collapse of the Alto Río building (Edificio Alto Río) in Concepción represents one of the most dramatic structural failures in the 2010 Maule, Chile Earthquake. The Alto Río was a 15-story apartment building constructed during 2008–2010 that housed 80 apartments and two underground parking levels. This reinforced concrete shear wall building completely collapsed onto its eastern face as a result of overturning. From visual inspection, the supporting shear walls at the ground level were too slender and inadequately reinforced to withstand the earthquake forces. The seismic loads imposed an overturning moment on the shear walls at the ground floor, leading to the loss of vertical carrying capacity in the first story above ground. After the failure of the shear walls, the east side of the building collapsed into the subterranean parking garage while the west side lifted off the ground. As it crashed onto its side, the building broke into two pieces between the ninth and tenth floors.

Because the earthquake struck in the early morning hours, many people were asleep at the time of the mainshock. Eighty-seven people were in residence, and the majority of those trapped made it to safety following the building collapse; 8 residents perished, and 27 had to be rescued from the debris. ■

Alto Río building before the 2010 Maule, Chile Earthquake (Source: http://concepcionunderconstruction.blogspot.com/2009/03/edificio-alto-rio-avances-22-2-2009.html)

The west side of the Alto Río building, illustrating the slender shear walls at the ground level. (Source: RMS)

Damage across the impacted region of central Chile, as captured by the RMS reconnaissance teams: (1) the 14-story Edificio Festival in Viña del Mar, built in 1978, suffered severe damage to the stairwells that span two sections of the building; (2) the end of this shear wall in the Edificio Festival ruptured under high compression loads and revealed an abundance of longitudinal reinforcement with little shear reinforcement; (3) buildings in the Huechuraba comuna of Santiago suffered heavy damage as a result of ground motion amplification in the basin; (4) the fire sprinklers at Santiago's International Airport released water over the main terminal; sprinkler systems contributed to contents and business interruption losses throughout the affected area; (5) a series of freeway overpasses in Santiago collapsed due to inadequate connections at the end supports; commuters were forced to use detours through side streets; (6) pedestrian walkways were on the brink of collapse at the main terminal of Santiago's International Airport; (7) the wine in these two storage tanks was salvageable, but nearly a dozen other tanks at this particular winery suffered total losses when they overturned or ruptured; (8) overturned wine tanks are piled along the property line at this vineyard's warehouse in Santa Cruz; inside, stacks of wine cases were filled with broken glass and spilled wine; (9) the entire front section of this landmark cathedral in Curicó collapsed during the earthquake; historic buildings, including many cathedrals, collapsed as a result of their highly vulnerable unreinforced masonry walls; (10) the first floor of this two-story home was entirely swept away and stuffed with debris when tsunami waves crippled the coastal town of Dichato; (11) at the University of Talca, thousands of books in the university library fell off the shelves and were drenched by the fire sprinkler system; (12) the chemistry lab at the University of Talca suffered heavy contents losses as lab equipment and materials fell off shelves and countertops; (13) the cooling towers at a petroleum refinery collapsed during the ground shaking, contributing to business interruption losses; (14) overturned cooling tower at a cement factory in Talcahuano shut down the plant for several weeks; (15) boats were swept down city streets and crashed into commercial buildings as a result of the tsunami waves in Talcahuano; (16) damaged and misaligned equipment at the cement factory in Talcahuano required months for inspections and repairs; (17) a distribution center in Chillán suffered heavy earthquake damage and subsequently lost an entire warehouse to fire following the earthquake; (18) several grain silos ruptured at a facility in Concepción; (19) the O'Higgins Tower in downtown Concepción suffered local, partial collapses in several locations; the building will have to be demolished; (20) the newly-constructed 15-story Alto Río building completely overturned during the earthquake; (21) severe damage to a confined masonry detention facility in Los Ángeles; attempts at escape by the prisoners were thwarted by guards.

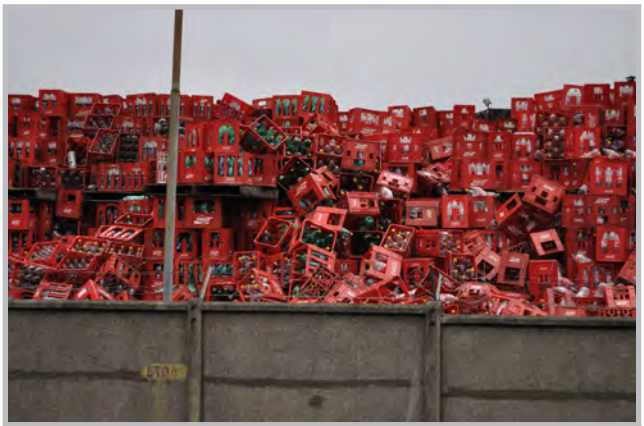
5 INDUSTRIAL PROPERTY DAMAGE

Industrial facilities were significantly impacted by the 2010 earthquake, generating business interruption (BI) losses from physical damage to structures and equipment; interruption of production due to lack of power, water, or supplies; and the need for detailed inspections before resuming operations. The RMS team inspected industrial properties, concentrated in the Biobío Region's ports of Talcahuano and Coronel, including cement plants, steel and glass manufacturing plants, chemical processing and refinery plants, pulp and paper mills, food processing plants, electrical substations, and power plants.

The team also inspected industrial facilities in the capital region, and found that most facilities had sustained minimal damage. For example, a power generation plant near Santiago and a refinery north of Viña del Mar were both operating at close to full capacity at the time of the RMS reconnaissance team's visit nine days after the event. A food processing plant in Casablanca, located about 30 km (19 mi) southeast of Viña del Mar, sustained minor equipment damage. In contrast, many of the industrial operations in Talcahuano and the other cities in the epicentral region sustained significant contents and equipment damage and were still non-operational in mid-March 2010.

5.1 Epicentral Region: Talcahuano

Talcahuano, located in the epicentral region of the 2010 earthquake, is a hub for heavy industrial operations. Business interruption affected facilities in this highly concentrated industrial area to varying degrees based on the size of the facility and the type of equipment, contents, and structures within the facility. For example, damaged high-end equipment requires specialized inspectors to examine and recalibrate the production lines, resulting in prolonged downtimes. Significant contents loss can occur in the absence of lateral bracing, as was observed at a soda bottling factory, where crates of glass bottles stacked 12 feet high with no lateral bracing collapsed in the earthquake. RMS teams also observed several collapsed light metal structures across industrial facilities in Talcahuano, which were among the most vulnerable industrial construction type to ground shaking damage. Notably, across the inspected industrial facilities, confined masonry buildings sustained much less damage than light metal buildings.



Damage to the stock of soda bottles in a facility in Talcahuano, Chile (Source: RMS)

5.1.1 Steel

The CAP steel manufacturing plant, Chile's largest steel mill facility, is located in Talcahuano. It employs 2,000 workers and an additional 2,000 subcontractors. Moderate nonstructural damage was observed in several buildings, and open dirt lots on the premises were strewn with various steel components. The facility was expected to be shut down for at least three months because of structural and equipment damage. In mid-June 2010, the company announced that steel output had resumed at the plant. Other facilities in Talcahuano, including a steel wire manufacturing facility and a cement plant, depend on this plant for supplies. During the shutdown, they were forced to seek other suppliers for their material needs.

5.1.2 Petroleum

The ENAP refinery in Talcahuano, built 45 years ago, produces approximately 116,000 barrels of petroleum per day. Physical damage to various components of the facility was observed, including some damage

Damage to an electric power substation at the ENAP refinery in Talcahuano, Chile (Source: RMS)

Collapse of a cooling tower at the Bío Bío cement factory in Talcahuano, Chile; fortunately, the failure of this tower did not impact the facility's production, as it was part of a backup system (Source: RMS)

to the cooling towers. At the time of the RMS visit in mid-March 2010, engineers were assessing the extent of the damage and suggested that the downtime for the facility could last for several months. In mid-June 2010, the company announced that the refinery would be operating at capacity by the end of the month. After reaching 100% capacity, the company estimated its losses at nearly $79 million. Similar to the CAP steel plant, neighboring industrial customers sought other suppliers, or had to suspend operations. For example, a small petrochemical processing plant that produces polypropylene sustained limited damage, but was non-operational due to its dependency on the ENAP refinery.

5.1.3 Cement

The Bío Bío cement factory, located across from the CAP steel manufacturing plant, employs 150 workers. The plant was originally built in 1960, with more recent additions built in 1998. At the time of the earthquake, only 10 employees were on site and there were no reports of injuries or fatalities. The plant resumed partial operations after three weeks of downtime, primarily caused by lack of power and the need for a damage assessment. This relatively small level of business interruption was fortunate, as the structures and equipment suffering major physical damage were not part of the facility's main production line.

The cooling tower collapse (in picture above) caused the flexural failure of a beam in the operations unit of the Bío Bío cement factory in Talcahuano, Chile (Source: RMS)

Overall, the cement plant sustained moderate physical damage that did not cause a long disruption to its functionality. The plant utilizes the city's electrical power, and its transformers had moderate damage. Engineers at the plant were concerned that aftershocks could snap transmission lines that were already under stress from the earthquake. The most noticeable physical damage was the collapse of a cooling tower, which was originally 50 m (164 ft) high and fell on a three-story reinforced concrete building. The falling cooling tower caused the complete collapse of the third story of the structure and extensive damage to the second floor control room. Had it not been for the flexural failure mode of a beam on the second floor, the damage would have been more severe (a flexural failure mode allows for large deformations; in contrast, a shear failure mode is sudden, resulting in a break of the structural element). The first floor of the building, which did not incur major damage, houses electrical control units for the plant. The cooling tower collapsed due to irregularities in the size of bolt connections between different sections of the tower. As a result, one of the sections failed, triggering collapse. In addition, lack of proper maintenance most likely contributed to the collapse. Fortunately, this failure did not impact the production capacity of the factory, since the cooling tower was a back-up system for the undamaged main drying system.

In the packaging section of the plant, severe damage was observed in a braced steel building, which housed office space. Failure modes included column buckling due to beams being stiffer than the columns, as well as buckling or failure of bracing at the connections to the columns. In addition, severe damage was observed in structures attached to the cement plant's silos, including the displacement of anchor bolts and buckling of the steel elements. In several locations in the facility, temporary fixes were in place to prevent the progress of physical damage and allow for faster resumption of plant production. For example, a conveyer system was shored up with a temporary support, as the original support had buckled as a result of the earthquake.

Failure of a reinforced concrete column as a result of lack of transverse reinforcement in the administrative office of the Inchalam wire manufacturing plant in Talcahuano, Chile (Source: RMS)

5.1.4 Galvanized Wire

The RMS reconnaissance team toured the Inchalam wire manufacturing plant in Talcahuano, which operates on a 24-hour schedule, 6 days a week, with 400 employees working in multiple shifts. With an annual capacity of around 120,000 metric tons of wire, this galvanized steel wire plant supplies different forms of wire to retail, wholesale, and distribution centers across Chile. The facility experienced an initial shutdown of ten days after the earthquake, primarily due to lack of power, community unrest (primarily looting), and site cleanup.

The building value for this facility is estimated at approximately $75 million, with an additional $125 million in equipment and contents. Within the facility, a confined masonry structure built in the 1950s houses the main production line. Building construction also includes newer light metal construction additions, housing the production line; a small reinforced concrete administrative office; a more recently built confined masonry warehouse of approximately 7,500 square meters; and a small cafeteria built in 1995. The reinforced concrete building housing the administrative office sustained significant damage and was unusable. The administration staff was relocated to several different areas throughout the facility. After closer inspection, it was concluded that the removal of portions of the original walls and partitions resulted in

Light metal roof failure at the Inchalam wire manufacturing plant in Talcahuano, Chile (Source: RMS) the loss of lateral capacity and inadequate structural performance.

With the exception of the heavily damaged reinforced concrete office building, overall structural damage to the facility was minor. For example, some of the facility's structures experienced damage to their elements, such as local buckling of two columns and a single steel beam failing. Temporary fixes were applied to the damage, so that the plant could resume production. In addition, damage to a small number of concrete crane supports was evident and was under repair at the time of the RMS visit. Roof trusses in another part of the plant were damaged due to the heavy weight of the wooden roof. The plant's operations manager indicated that the roof was going to be replaced using lighter corrugated metal.

5.2 Epicentral Region: Other cities in Biobío and Maule regions

Coronel, a port city south of Talcahuano and Concepción, also has a high concentration of industrial facilities dependent upon one another. RMS reconnaissance teams visited Coronel, as well as other cities in the Biobío Region with industrial plants, including Arauco, Chillán, and Los Ángeles. Industrial facilities in this region include power plants, pulp and paper mills, a glass manufacturing facility, and other light industrial facilities. The team also surveyed tsunami damage along the Bay of Concepción.

In Penco, located east of Talcahuano on the Bay of Concepción, tsunami damage to light industrial facilities had occurred. Employees at an unoccupied coastal warehouse said that the tsunami struck the property in three waves approximately two hours after the earthquake, with the third wave being the highest. Fortunately, employees were able to evacuate to higher ground while the waves swept through the warehouse and carried steel silos off their foundations nearby.

Tsunami damage in an industrial facility in Penco, Chile (Source: RMS)

Observed damage to the Lirquén glass manufacturing facility in Penco, Chile (Source: RMS)

5.2.1 Power Generation

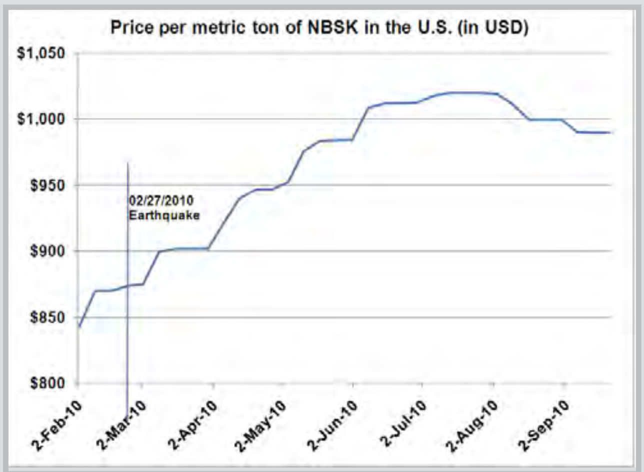
A newer power plant, operated by Endesa and located south of Concepcion, employed 2,400 workers. At the time of the earthquake, 250 employees were working the night shift; fortunately, none of the employees were injured. According to a preliminary assessment, there were no signs of major damage. However, the interruption of power generation was expected to last at least three months in order to complete a structure and equipment inspection. Another power plant, still under construction at the time of the earthquake, sustained some physical damage in the anchors of the metal frame housing the turbine. The completion of the power plant, which began construction in 2008, will be delayed because of this damage.

5.2.2 Glass

Moderate building and equipment damage to the Lirquén glass manufacturing facility in Penco was also surveyed. The roofs of some older storage facilities, mainly used for storing sand, had collapsed because the small steel columns supporting the roof were shaken from the main concrete columns. At least five storage tanks, all sitting on one reinforced concrete frame, tilted because the supporting columns of the pedestal failed during the earthquake. Approximately 100 tons of glass fell off the shelves in the warehouse. The most expensive loss was the main oven, which will need to be replaced. In March 2010, the plant was expected to be non-operational for at least four months. The following month, the company announced that the oven was being redesigned and the facility was expected to resume operations by the end of the year.

Chilean Pulp Industry

The Chilean pulp industry is a major global producer of cellulose, accounting for approximately 8% of the world's supply. Pulp mills are concentrated in this region due to the dense concentration of wood forests. Global prices for pulp and paper began to rise after the February 27, 2010 event. While prices had been increasing since May 2009, with heightened demand from China, the earthquake—in conjunction with a Finnish port strike—caused additional shortages. For example, the price of Northern bleached softwood kraft (NBSK) pulp, approximately $640 per metric ton in May 2009, reached $900 per metric ton on March 9, 2010. In July 2010, prices peaked at $1,020 per metric ton, until mid-September 2010, when prices dropped to $990 per metric ton. In June 2010, some industry analysts predicted that pulp prices would begin to flatten, as Chilean pulp once again became available and demand from China slowed. One year later, prices remain relatively flat, hovering between $990 per metric ton and $1030 per metric ton in the summer of 2011. ■



Price per metric ton of NBSK (Northern bleached softwood kraft) pulp in the U.S. from early February 2010 through mid-September 2010, based on FOEX's PIX benchmark price index (Date Source: FOEX Indexes Ltd.)

5.2.3 Pulp

Several pulp manufacturing facilities in the Biobío Region were still completely shut down in mid-March of 2010. Although the level of physical damage to these facilities was minimal, the level of BI loss is significant. The primary contributor to BI for the pulp and paper facilities in Chile is the need for detailed inspections in order to calibrate the production lines.

One pulp mill in Laja, shut down at the time of the team's visit, employed about 400 people, with an additional 400 sub-contracted workers. The plant site is a 90-hectare heavy industrial facility, which includes manufacturing equipment as well as storage and administrative buildings. The earthquake triggered an automatic shutdown of the facility, and the plant's operation team had completed inspections of the structures and equipment, but was awaiting more comprehensive inspections by Chilean structural engineers and foreign manufacturers of the equipment. Outside inspection teams were in high demand, as many industrial and commercial owners requested their assistance in assessing the safety of inhabiting damaged buildings or resuming production operations.

The in-house inspection team concluded that the older reinforced concrete buildings built prior to 1970, as well as the newer light metal structures, sustained no major structural damage. At the time of the RMS visit, there was no water service or municipal electricity; the plant was generating its own power. The plant was closed for over a month, largely due to the equipment inspection, until on April 1, 2010, the company announced that the plant was operating at full capacity. For this plant, the equipment inspection was extremely critical; had any component sustained major damage, the equipment would have to be repaired or re-manufactured overseas. These requirements would have kept the facility from resuming normal operations for another six months to one year.

The RMS team visited several other pulp and paper plants. One plant's operator, who managed two production lines, estimated that one line would be

A pulp mill shutdown as a result of the earthquake in Laja, Chile; the plant was awaiting a detailed inspection before resuming operations (Source: RMS) completely shut down for 1 to 2 months and the second line for at least three months. Another paper mill south of Coronel had experienced some physical damage to its production lines—with downtimes expected to last at least eight months. Unlike other facilities, several employees were injured at this plant. Industrial facilities also sustained damage from tsunami waves, as observed at a paper mill in Constitución, where tsunami waves had caused some tanks to buckle and scatter debris in the plant yard.

5.2.4 Food and Beverage

Other industries sustaining significant contents and equipment damage in the Maule and Biobío regions included wineries, soda bottling companies, and other light manufacturing facilities. At one soda bottling facility near Talca, two of the five tanks collapsed and some of the processing equipment was out of alignment. The collapse of silo structures (e.g., for storage of grain and wine), was evident across the region. The failure modes of the silos included the rupturing and bulking of the shell; the failure of the base support; buckling of the supporting columns; shear failure of the bracing systems; and rupturing of the cylindrical shell elements. Failures to all sizes of grain silos (up to 5,000 tons) were observed; however, failures were associated with full silos only. At one grain mill in Concepción, numerous damaged silos, as well as structural and equipment damage, were observed. It was unknown how long production would be idle; however, the repair time for a failed grain silo (i.e., to extract grain from silo, remove damaged silo, and reinstall a new one) at the mill was expected to be two months.

At wineries, the buckling of the supporting columns was the most prevalent failure mode observed. Chile is famous for its excellent wines and takes great pride in their abundance and quality. In the heart of Chile's wine country, between San Fernando and Santa Cruz, numerous wineries sustained heavy damage to structures and equipment. One winery in the Santa Cruz region lost over 20,000 liters of wine due to the collapse of stainless steel storage tanks. In the first week after the earthquake, wineries assessed the damage and organized their workforces to resume operations where possible. Damage to roads, communication systems, and workers' homes posed significant obstacles to this process. With harvests scheduled for just a month after the event, many wineries were under particular pressure to resume work as soon as possible.

The most common form of winery damage was tank failure. According to interviews with local workers, similar tanks are used at nearly every winery in the country. These tanks typically have capacities of 30,000 to 40,000 liters and are constructed of stainless steel. The cylindrical tanks are supported on legs, many of which rest upon a small steel pin. These small pins appear to have been the first point of failure for many tanks. Once the pin fails, the tank moves

Failure of grain silos near Coronel, Chile (Source: RMS)

Damage to stainless steel storage tanks resulted in considerable amounts of contents loss to the Chilean wine industry (Source: RMS)

Close-up of the support failure in a cylindrical stainless steel wine storage tank (Source: RMS)

Location	Normal Consumption (MWh-day)	Consumption immediately after event (MWh-day)	Percentage of Normal Consumption
OxyChile Talcahuano Plant	*492*	*13*	*3%*
CAP Huachipato	*1,563*	*81*	*5%*
Dow Petrochemicals - SA	*120*	*6*	*5%*
Eka Nobel	*411*	*6*	*1%*
CMPC Charrua Plants	*2,242*	*332*	*15%*
Inchalam	*90*	*66*	*73%*
Molycop	*150*	*3*	*2%*
Bío Bío Refinery ENAP	*768*	*72*	*9%*
Cementos Bío Bío	*145*	*145*	*100%*
Masisa Cabrero	*259*	*12*	*5%*
Masisa Mapal	*255*	*53*	*21%*
Bío Bío Norske Papers	*720*	*14*	*2%*
Petroquim	*144*	*12*	*8%*
Indura - Lirquén	*111*	*99*	*89%*
Indura - Graneros	*84*	*79*	*94%*
Total	***7,554***	***993***	***13%***

Summary of power outages: reduction in electricity consumption at various industrial facilities in Chile in the aftermath of the 2010 earthquake (Source: Government of Chile)

downward and the supports fail at the connection to the tank. This type of failure was observed in numerous tanks at many wineries. ■

Chilean Wine Industry

Following the 2010 Maule, Chile Earthquake, Vinos de Chile (VDC), the industry association of Chilean winemakers, estimated that approximately 125 million of liters of wine worth up to $250 million were lost in the earthquake due to the collapse or overturning of storage tanks and the breaking of oak barrels and bottles. In further assessments of the impacts, losses to the wine industry's infrastructure (e.g., damaged irrigation systems and cellars, collapsed canals), including damaged oak barrels, were estimated at $180 million. Therefore, the total loss was approximately $430 million, of which an estimated 90% will be covered by earthquake insurance (Rabobank, 2010).

In 2009, Chile was the fifth largest exporter of wine in the world. The loss of 125 million liters of wine represents approximately 12.5% of the 2009 national production of 986 million liters. However, if one considers the 2009 export values of 695 million liters, this loss represents 18% of Chilean wine sold to other countries. Unfortunately, before the February 27 earthquake, wine production was expected to be 15% less than the 2009 season, due to spring freezes and a cooler summer. At the time of the earthquake, some wineries had begun harvesting grapes with others preparing to do so, as harvesting season runs from March through May. The main concerns for the 2010 season were damaged irrigation systems and labor availability. A drop in wine-related tourism was a concern of the VDC as well. In early April 2010, when the Colchagua Valley often hosts many wine festivals, less than half of the vineyards were open to tourists and most festivals were cancelled. Wineries in this particular region are part of touring packages that include winery tours, upscale hotels, and a casino in Santa Cruz. ■

6 RESIDENTIAL PROPERTY DAMAGE

Damage to residential properties in the 2010 Maule, Chile Earthquake ranged from negligible damage to complete collapse. Along the coast, destruction from tsunami waves dominated the damage patterns, with inland communities suffering primarily from the event's ground shaking. While residential structures in regions V through IX (i.e., from Valparaíso to La Araucanía, as described in Section 2) were constructed using a variety of materials (e.g., adobe, masonry, reinforced concrete, timber), the most significant damage surveyed by RMS reconnaissance teams occurred in adobe and unreinforced masonry (URM) structures. Numerous partial and total collapses of these types of buildings were evident across the region.

According to the Chilean Housing Ministry's Programa de Reconstrucción Nacional en Vivienda (National Housing Reconstruction Program), approximately 370,000 households were impacted by the event, with over 81,000 homes destroyed and another 289,000 sustaining damage. Of the 81,000 destroyed homes, over 50,000 of them (i.e., 60%) were adobe structures. With over 133,000 of the homes in regions V through IX constructed of adobe, approximately 38% of the adobe residential building stock was destroyed in the event. Because of their high vulnerability to earthquakes, collapsed adobe homes were present in every city visited by RMS reconnaissance teams—from Concón in the north to Los Ángeles in the south.

The remaining Chilean housing stock, consisting primarily of wood frame, confined masonry, or reinforced concrete frames with unreinforced masonry infill walls, generally performed much better than adobe and unreinforced masonry buildings. While major damage was observed in some cases, there were few instances of complete collapse. Because of their light weight and structural ductility, wood frame structures sustained less damage than heavier masonry structures, which are generally more stiff and brittle. Confined masonry structures also demonstrated good earthquake performance. For example, in the Biobío Region, a confined masonry home with wood framing at the second floor sustained no damage, even though it was located fairly close to the rupture zone in the city of Coelemu.

Housing Type	Destroyed Houses	Houses with Major Damage	Houses with Minor Damage	Total Affected Houses
Coastal	7,931	8,607	15,384	31,922
Adobe (Urban)	26,038	28,153	14,869	69,060
Adobe (Rural)	24,538	19,783	22,052	66,373
Group Housing (Government)	5,489	15,015	50,955	71,459
Group Housing (Private)	17,449	37,356	76,433	131,238
Total	**81,444**	**108,914**	**179,693**	**370,051**

Residential damage estimates for affected regions of Chile as of March 2010 (Source: Government of Chile)

6.1 Tsunami Damage

Along the tsunami-impacted coastline, inundation caused severe damage to all types of residential structures (e.g., wood frame, confined masonry, and unreinforced masonry). The majority of impacted exposure was at an elevation of 5 m (16.4 ft) or less. In the fishing village of Dichato, located approximately

Collapsed adobe residential structure in Santa Cruz, Chile (Source: RMS)

Destruction along the coastline in the town of Dichato due to tsunami waves following the 2010 Maule, Chile Earthquake (Source: RMS)

Aerial view of the city of Dichato before the tsunami waves (left) and after the tsunami waves (right), illustrating the complete destruction of buildings in their path (Source: http://www.emol.com/especiales/2010/fotos_AD/terremoto_antesydespues/index.htm)

50 km (31 mi) north of Concepción, more than 75% of the village was destroyed by the waves. According to eyewitness accounts, three waves reached the shoreline. While the first two waves did not cause much damage, the last one measured close to 10 m (33 ft) in height and destroyed structures in its path.

The community of Dichato had a frontage road for beach and boat access, as well as a low seawall (less than 2 m or 7 ft) along the southern part of the beach. As a result, the highest coastal damage occurred along the northern part of the beach, where there was no seawall. The tsunami damage in Dichato extended inland more than 750 m (0.5 mi). The worst of the inland inundation was along the Rio Dichato (Dichato River), which funneled water into and out of the village as the tsunami waves hit the coastline.

6.2 Reconstruction Efforts

At the end of March 2010, the Chilean government launched Chile Unido Reconstruye Mejor (Chile United to Rebuild Better), a housing reconstruction program designed to meet both the short and long-term housing needs caused by the February 27, 2010 event. The program provides two types of housing subsidies—one for the construction of new homes and one for the repairs to damaged homes—over the next three years. Once temporary emergency housing is complete, a reconstruction phase for permanent housing is expected to continue through 2013. The plans aim to assist 323,000 of the 370,000 affected households at a total cost of $3.9 billion.

The reconstruction program identifies seven categories of housing solutions to be implemented (Ministry of Housing and Urban Development, 2010):

1. Reconstruction of severely damaged multi-family dwellings that were constructed and financed by the government (SERVIU housing);
2. Solutions for homeless, low-income Chileans without title to property;
3. Reconstruction of coastal areas destroyed by the tsunami;
4. Support for families that owned rural or urban adobe homes that collapsed or were severely damaged;
5. Reconstruction of housing located in historical sectors;
6. Financing for displaced families that did not have earthquake insurance but are credit-worthy; and
7. Subsidies for low-income families living in houses that need repairs.

In the affected regions, housing reconstruction and repair programs are expected to mitigate future risk associated with earthquake and tsunami hazards. Materials and construction practices that performed poorly in this event (such as adobe and unreinforced masonry) are likely to be avoided in the future. Some engineered buildings, such as those constructed using reinforced concrete shear walls, also sustained significant damage and are being studied by local and international engineers with hopes to learn lessons regarding their design and construction. RMS will continue to monitor the reconstruction efforts in Chile to evaluate the vulnerability of structures that were built before and after the event. ■

7 PUBLIC BUILDING DAMAGE

A wide range of damage was sustained in public buildings, including elementary and secondary schools, universities, hospitals, historic churches, and government buildings. Government buildings such as city halls, municipality buildings, and courthouses generally performed well. One exception was a courthouse in Talca, which closed for approximately one month for cleanup.

Schools across the country were closed for over a week following the event, with children attending class again on Monday, March 8. In the worst-affected regions of Maule and Biobío, students were out of school for many weeks. While the Chilean government's deadline of April 26 to return all children to their classrooms was met, some students whose schools were destroyed in the earthquake, were in makeshift classrooms (in tents and buses) and others were sharing classroom space with students in operational schools.

Thousands of schools were in need of repairs—both minor and major. Many school buildings sustained damage to classroom contents, while other schools sustained significant structural damage as well. For example, one reinforced concrete frame school building in the Santiago region had extensive structural damage to its reinforced concrete columns. A common failure mode, in which "short columns" sustain the majority of the lateral deflection, was evident. The infill walls prevented the structural columns from bending side-to-side; when the floor above and the floor below moved relative to one another in the earthquake, the short columns experienced much higher shear forces than if the walls had not existed. Damage of this type compromises the structure's stability and renders the building unsafe for occupation.

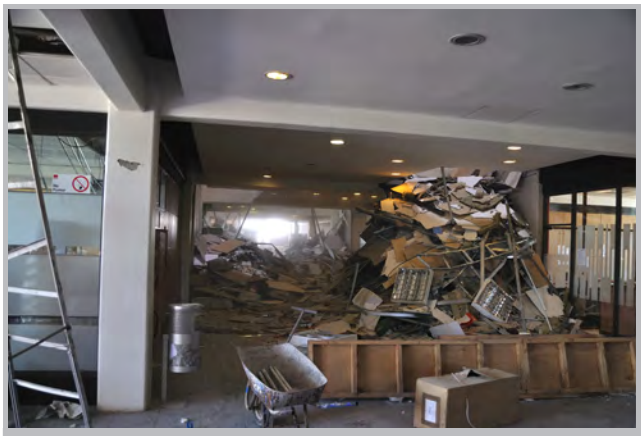
Damage to a chemistry building on the University of Talca's campus: a section of the roof detached from the wall and collapsed onto the walkway below (Source: RMS)

7.1 Universities

RMS reconnaissance teams visited two campuses in the epicentral region, observing moderate to major structural building damage and extensive damage to contents and nonstructural elements. At the University of Talca (Universidad de Talca), the dean of the law school estimated that it would take $10 million to repair the buildings and replace destroyed contents, including laboratory equipment, computers, and library books. In particular, books that fell from library shelves sustained additional water damage from the building's sprinkler system.

At University of the Americas (Universidad de las Américas), a private university in Concepción, the primary classroom and administrative building sustained very high losses that were concentrated at the top floor. The building consisted of a four-story, reinforced concrete structure with a one-story steel structure that was constructed three years later

Damage to reinforced concrete "short columns" in a school building in the Santiago region (Source: RMS)



A massive pile of debris was extracted from a building on the campus of the University of the Americas in Concepción, Chile (Source: RMS) and served as the top floor of the structure. The earthquake caused the steel columns to buckle near the top of the columns at the roof line. Extensive contents and nonstructural components damage increased with each floor, with particularly severe damage to elements on the top level (primarily due to the discontinuity in floor accelerations between the top steel frame floor and the lower reinforced concrete floors).

The collapse of ceiling tiles and interior wall partitions, as well as the overturning of laboratory equipment, classroom furniture and fixtures, computers, and medical training equipment, was observed. Because of this damage, particularly within the fifth floor steel structure, the entire building was rendered unusable while rubble was removed. Improper anchorage and lack of bracing were the primary causes of the high contents damage.

7.2 Hospitals

Hospitals across the impacted region sustained damage, disrupting the care of patients and in some cases, limiting the response of the medical community to those injured in the earthquake. At the end of March 2010, the Minister of Health reported that a total of 130 hospitals were damaged in the event, with 54 hospitals sustaining minor damage, 8 hospitals experiencing major damage and requiring structural repairs, and 17 hospitals sustaining extensive damage and necessitating reconstruction. Overall, losses were estimated at $2.7 billion (PAHO, 2010).

At a hospital in Curicó, located northeast of the epicenter, patients were evacuated from portions of the facility due to concerns about the integrity of the structure and loss of functional capacity, including medical equipment. The hospital had been constructed in two phases, with one much older structure connected to a newer, more modern one. The older wing of the building was heavily damaged and had been evacuated, while the newer wing was in use following the event, though overcrowded. At the time of the RMS team's visit, a temporary field hospital had been set up next door to meet the demand for medical care in the region.

7.3 Historic Masonry Structures

Museums, churches, and other historic masonry structures sustained out-of-plane failures in unreinforced masonry walls, cladding damage, and parapet and other roof connection failures. For example, the Basilica Del Salvador in Santiago, constructed in the 1870s and previously damaged in

With a hospital in Curicó, Chile, severely damaged, tents were set up to accommodate patients (Source: RMS)

the 1985 earthquake, was further compromised in the 2010 event. The building's façade lay in rubble at its base. Also in Santiago, large pieces of the façade on the west side of the Museum of Fine Arts had fallen, damaging the stairs below. Throughout central Chile, historical churches were disproportionately impacted by the event, as most were unreinforced masonry or adobe structures and particularly susceptible to earthquake damage. In Curicó, a church's tower had collapsed onto the roof, causing the roof to collapse as well. All that remained of a church in Peralillo were two stark white columns. In Santa Cruz, the city's main abode church, constructed 165 years ago, was heavily damaged and scheduled for demolition. The church's padre was confident it will be rebuilt, similar to its original design. ■

Damage to a historic church in Curicó, Chile: collapse of the Iglesia San Francisco's front tower and entrance (Source: RMS)

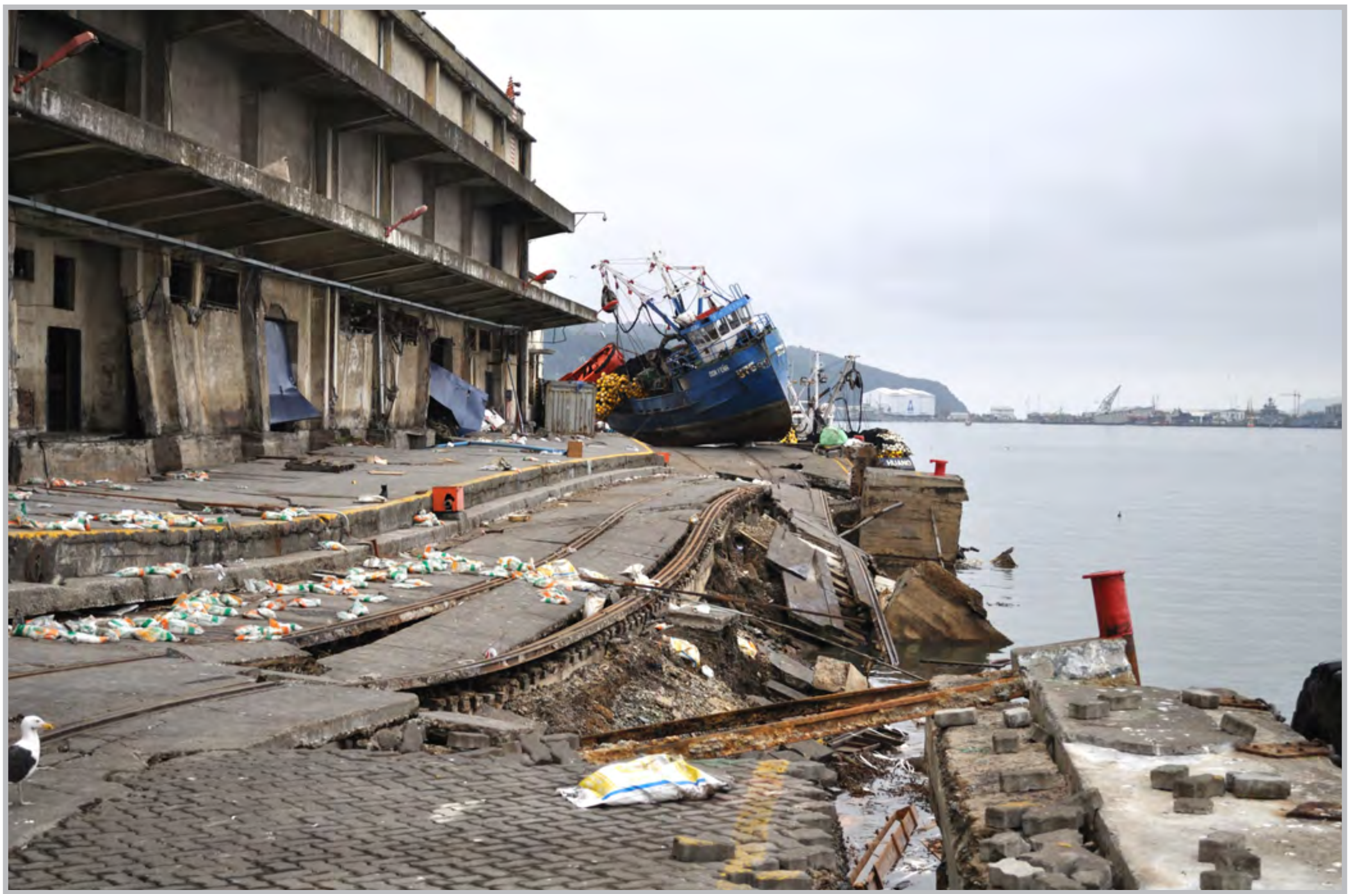
8 INFRASTRUCTURE DAMAGE

The RMS reconnaissance team observed damage to several components of Chile's civil infrastructure, including seaports, airports, highways and bridges, as well as lifeline networks (e.g., water supply, electric power, telecommunications). In addition to direct costs associated with repairs, infrastructure damage incurs secondary costs when it prevents daily life and industry from operating at full capacity. The most significant losses associated with infrastructure damage in Chile came from damaged ports, airports, highways, and bridges. Service interruptions of electric power, telecommunications, and the water supply are also discussed in this section.

8.1 Ports and Harbors

Ports and harbors throughout the epicentral region sustained extensive property and contents damage as a result of the earthquake and tsunami. Very heavy damage was experienced at the Talcahuano and Coronel ports, as well as the smaller ports in Penco, Tomé, and Constitución. The country's busiest port in San Antonio, located just north of Llolleo, sustained some structural and equipment losses that closed the port for several days. After two weeks, however, the port was able to restore most of its operations using eight of its nine berths. The other principal port in Valparaíso sustained moderate damage that shut down its operations in the days immediately following the event. Tourist operations were suspended for over a week and 90% capacity was achieved within two weeks, though only six of the port's eight docks were operational.

The port in Talcahuano is comprised of public, private, and naval port facilities that all sustained extensive damage in the earthquake and subsequent tsunami. Various sources have estimated the repair cost at more than $100 million. Several berths were destroyed and the ASMAR shipyard was at minimal capacity, having sustained extensive physical and time element losses. Response and repair efforts at the Talcahuano port were hindered for several days due to inoperative communications systems. The RMS team observed dozens of ships that had washed ashore, many of which had collided with buildings, bridges, and power lines. The tsunami waves also carried



Destruction of the port facilities in Talcahuano, Chile (Source: RMS)

Damage to the port in Coronel, Chile (Source: RMS)

ships and containers across the Bay of Concepción. Along the coastline in Penco, two containers (weighing approximately four tons each) had originated from the Talcahuano container port. A marine ship was also swept across the bay and was grounded on the Penco beach—approximately 5 km (3.1 mi) from where it was originally moored.

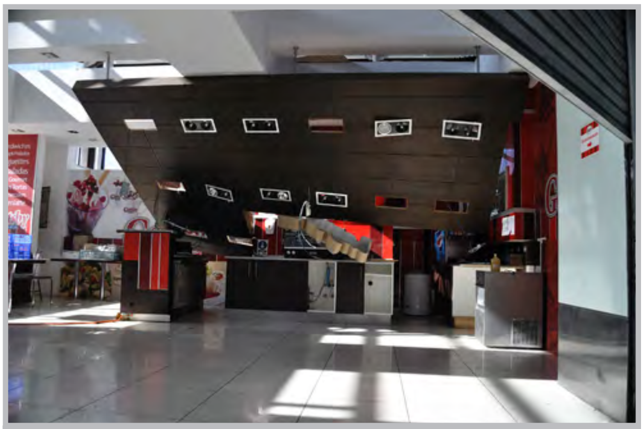
At the port in Coronel, physical damage to the structural piers and containers was observed by the RMS reconnaissance team. In a storage area at the port, 30 containers filled with timber products had fallen into the ocean. Moreover, several of the six major piers were still out of service three weeks after the event, due to the damage to their support systems. One pier used by the local fishermen had collapsed, causing significant business interruption (BI) losses to the regional fishing industry. Other BI impacts were expected, as railways that connected this port to suppliers were damaged, forcing local companies to use trucks for shipping their goods.

8.2 Airports

The RMS team inspected damage at both the Santiago International Airport (SCL) and the Carriel Sur International Airport (CCP) in Concepción. The Santiago International Airport, officially known as the Comodoro Arturo Merino Benítez International Airport, is the largest aviation facility in the country, and on a daily basis, accommodates approximately 100 international and 130 national flights. The airport sustained almost no damage to its structural system, but significant damage occurred to ceilings, cladding, pedestrian bridges, and mechanical/electrical equipment. The fire sprinkler system automatically engaged after the earthquake and drenched the entire main terminal building. Operations were shut down for 48 hours following the earthquake; however, a small amount of domestic and international flights were allowed to both arrive and depart from the airport.

Over the course of the following month, the airport slowly built up to full capacity. On March 3, the airport opened to passenger flights—with restrictions—and national flights were operating at 60% capacity. Temporary structures and services were enabled for these limited flights, and the shipping terminal, accommodating both national and international goods, was opened at this time as well. On March 5, the first of two RMS teams landed at SCL. By March 8, the airport was at 80% capacity and the international arrivals building was opened. And on March 29, SCL was operating at full capacity with all buildings open and shops, restaurants, and other services available for passengers. LAN Chile, which is Chile's largest airline, estimated the net impact of decreased passenger operations at approximately $25 million during the first quarter of 2010.

In Concepción, Carriel Sur Airport (CCP) was a well-designed steel structure that sustained no significant structural damage and minor to moderate damage to nonstructural elements and contents. For example, the sprinkler pipes caused damage to the ceiling, but did not leak or cause any water damage to the floor below. Retail stores in the terminal building lost inventory due to the ground shaking. The airport was closed for minor repairs and inspections, but the damage did not disrupt the airport's activities for more than a few days. While the National Office of Emergency of the Interior Ministry (ONEMI or Oficina Nacional de Emergencia del Ministerio del Interior) reported no communication with CCP in the days following the earthquake, by March 8, the airport was at normal operating conditions. At the time of the RMS visit on March 10, the airport was being utilized for

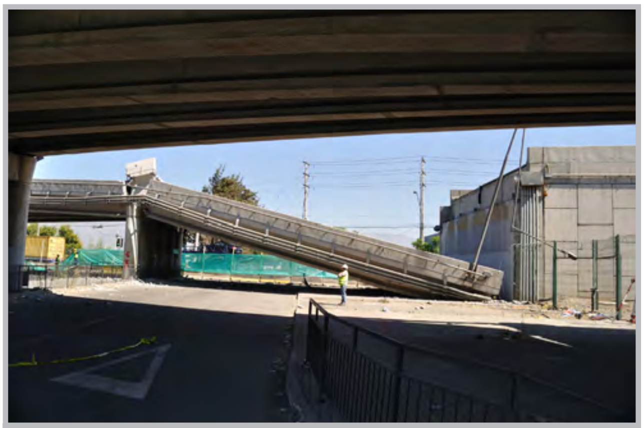


A suspended ceiling fell onto the counters of an airport cafe in the Comodoro Arturo Merino Benítez International Airport (Santiago International Airport) (Source: RMS) both relief supplies and passenger travel.

8.3 Roadways and Bridges

Ground failures were responsible for hundreds of damaged roadways throughout the affected area. RMS team members observed these failures (many due to poor soil compaction) along their reconnaissance route—particularly between Santiago and Los Ángeles. On Chile Highway 5 (Ruta 5), which is part of the Pan-American Highway and serves as a primary shipping route for trucks, dozens of large scale ground failures created massive fissures and forced traffic to either take detours or share one side of a divided highway.

Bridge damage across the region was primarily due to insufficient seismic connections (that failed during strong ground shaking) and/or soil failure at the abutments (mainly due to lateral spreading). Along the Autopista Vespucio Norte Express, a highway connecting the Santiago International Airport to the downtown area, the RMS team observed no less than five bridge/overpass failures. Each collapse was a result of insufficient end support for the bridge deck/girder system, with the joint at the end connection failing. The damage to the highway system significantly slowed traffic into and out of the city.



Collapsed span of the Autopista Vespucio Norte Express, connecting the Santiago International Airport to downtown Santiago (Source: RMS)

Bridge damage was also observed between Santiago and Concepción on Ruta 5. A historic bridge over the Río Claro, located between Curicó and Talca and constructed of unreinforced masonry, collapsed due to deficient lateral resistance. Another bridge, located a few kilometers southwest of Chillán, had insufficient connections between its spans, causing a section of the deck to shear off—onto the ground below.

Closer to the epicenter in Concepción, several bridges connecting Concepción to San Pedro de la Paz across the Biobío River were damaged. The supporting piers of the Juan Pablo II Bridge (also known as the Puente Nuevo or New Bridge), sustained

Collapse of an unreinforced masonry bridge, located between Curicó and Talca along Chile’s Ruta 5 and spanning the Río Claro (Source: RMS)

Buckled roadway along Chile Highway 5 (Ruta 5), south of Santiago (Source: RMS)

shear failure. Damage appeared to be the result of inadequate shear reinforcement, compounded by poor soil conditions. Through visual inspection, the RMS team found evidence of liquefaction (sand boils) near the approach to the bridge. Nearby, the Biobío Bridge (also known as the Puente Viejo or Old Bridge) completely collapsed. Originally built in the 1930s and used only for pedestrian traffic, numerous slab sections fell into the river. The Llacolén Bridge, constructed in 2000 and spanning the river between the Juan Pablo II and Biobío bridges, sustained deck unseating. Inadequate connections at the bridge abutment appear to have caused the failure. At the time of the RMS visit, a temporary metal bridge was installed by the Chilean military to facilitate traffic crossing the river.

After the earthquake, online forums and crowd-sourcing sites emerged that contained organized information about damaged roadways and bridges. For example, one mapping site (http://www.kom.cl/?a=1254) tagged locations according to the level of damage: green (no damage), yellow (roads passable with caution), or red (dangerous conditions and heavy damage). In addition, the Chilean Ministry of Public Works (Ministerio de Obras Públicas or MOP) created a blog with the latest information on road and bridge closures and the status of infrastructure reconstruction plans (http://mopinforma.blogspot.com).

8.4 Lifeline Networks

Outside of the worst hit regions of Maule and Biobío, the power, water, and telecommunications systems performed fairly well in the 2010 earthquake. Within the worst hit regions, RMS reconnaissance teams observed several instances in which damage to lifeline networks compromised a company's ability to conduct normal business operations. For example, winery

Evidence of liquefaction (sand boils) near the Juan Pablo II Bridge, which spans the Biobío River and connects Concepción to San Pedro de la Paz (Source: RMS)

owners could not contact their workers due to the lack of telephone service and cement plants could not operate without power.

8.4.1 Electricity

The electricity industry is largely privatized in Chile. Electricity transmission and distribution takes place through four regional electric power grid systems, each servicing a different section of the country (U.S. Department of Energy, 2010). The northern grid, Sistema Interconectado del Norte Grande (SING), accounts for close to 20% of nationwide electric power generation. Central Interconnected System (SIC), the central region's grid, serves 93% of Chile's population and accounts for the majority of the power generation. The Aysén and Magallanes grids, both in southern Chile, generate the remaining power. The RMS reconnaissance team observed localized cases of transmission lines failures and transformer damage, as well as damage at power generation plants, which caused service interruptions.

One day after the earthquake, media reports estimated that more than 80% of customers in the Santiago and Valparaíso regions and 50-60% in the O'Higgins Region had power. On March 10, the Pan

American Health Organization (PAHO) reported that electric power systems were operating at 95% in the urban areas of the Maule Region, with the exception of Constitución, where the supply was intermittent and functioning at 40% capacity. PAHO also reported that electricity was functioning at 80% capacity in the Biobío Region, although Concepción, Talcahuano, and Coronel were at 50% capacity. On March 14, approximately two weeks after the earthquake, the failure of a transformer within the SIC network left most of the country without power. While power was restored in a few hours in most areas, the outage continued into the next day. The government indicated that the outage was not directly related to the earthquake, but the blackout highlighted the need for resiliency within the grid network.

8.4.2 Natural Gas

Natural gas is distributed in Chile through an extensive network of underground pipelines, originating in Argentina. Gas pipelines are designed for the active seismic environment with special requirements for intersections, canals, and so forth. Damage to pipelines in Chile was fairly limited. For example, following the earthquake, Metrogas Chile, the distributor of natural gas to the Santiago metropolitan area, reported no natural gas distribution or supply problems.

8.4.3 Water

From March 2 through March 28, the Chilean government released daily reports on potable water availability throughout the impacted regions (Valparaíso, Santiago, O'Higgins, Maule, Biobío, and La Araucanía). While on March 2, 95% of the inhabitants in the Valparaíso, Santiago, O'Higgins, and La Araucanía regions had access to potable water, only 62% and 44% of the population in Maule and Biobío, respectively, had water. By the end of March, water service was restored to all regions; however, in the hardest hit rural regions, access to drinking water was still very irregular or being supplied through tanker trucks.

8.4.4 Telecommunications

From March 1 through March 12, the Chilean government's Undersecretary of Telecommunications (Subsecretaría de Telecomunicaciones or Subtel) provided daily updates on the status of the mobile and fixed telecommunications networks. Initial service interruptions in some areas were due to the interdependency between telecommunications and

Failure of an overhead transmission line in Lota, Chile (Source: RMS)

electric power supply. For example, the mobile and fixed networks in Maule and Biobío were limited in the days following the earthquake (operating at less than 30% capacity) because of lack of electric power supply, fallen fixed network distribution poles, and congestion. In contrast, two days after the earthquake, the Valparaíso and Santiago regions had mobile phone stations operating at 65%, with the fixed networks faring better at 80% or more. Within a week, mobile and fixed networks in the Valparaíso and Santiago regions were operating at 95% or better. In the Maule and Biobío regions, Subtel reported that approximately 90% and 80% of mobile radio bases and over 95% and 90% of the fixed networks were operating, respectively. ■

9 LOSSES AND MODELING INSIGHTS

The 2010 Maule, Chile Earthquake was not unexpected, occurring along a known “seismic gap” of the subduction zone off the coast of Chile. It was the largest event to occur since the 1960 earthquake and similarly devastated portions of the country. While seismic design and construction practices in Chile are among the best in Latin America, the ground shaking and tsunami damage to public and private property, as well as the loss of life, was sizeable—estimated at over $30 billion in economic loss and 520 casualties. In this section, a summary of the impacts from the event are presented, along with the implications for catastrophe modeling and the global insurance industry.

9.1 Economic Losses

In late March 2010, the U.N. Office for the Coordination of Humanitarian Affairs (OCHA) estimated that 1.8 million people were affected by the earthquake and tsunami, causing approximately $30 billion in loss to the Chilean economy. Also at this time, the Chilean government’s loss estimate was issued, totaling $30 billion, which included $10.6 billion in damage to the public sector (e.g., schools, hospitals, housing), $10.4 billion in damage to the private sector (e.g., industrial and commercial enterprises), $7.6 billion in loss to the Gross Domestic Product (GDP) through 2013, and $1.0 billion in other expenses.

According to the Global Competitiveness Report (GCR) for 2009–2010, Chile has the most competitive economy among Latin American countries, and ranks 30th in the world. In the first quarter of 2010, Chile’s GDP was estimated by the Central Bank of Chile at $176 billion, which translates to an earthquake loss representing 17% of GDP. The hardest hit regions of Maule and Biobío, contributing 14% of the country’s GDP, contained concentrations of the manufacturing and fishing industries. The manufacturing sector, which accounts for 13% of GDP across the country, includes industrial facilities visited by the RMS team, such as pulp mills and steel manufacturing plants.

Given this enormous impact on the GDP, rebuilding efforts will require many years and significant international loans. The Chilean government is planning to cover approximately $12 billion of the total cost of $30 billion over four years, which represents $9.3 billion in reconstruction and $2.4 billion in fiscal recovery. It is expected that insurance and contributions from the private sector will cover the remaining reconstruction costs. In order to help finance the recovery costs, the Chilean government announced in April 2010 that it would issue bonds to the international financial markets. And in late July, Chile placed 10-year bonds worth $1 billion, as well as peso-denominated debt, in the marketplace.

9.2 Insured Losses

Insurance played a role in event recovery, as earthquake insurance is a common practice in the seismically active country of Chile. The 2010 earthquake represents a major event for the global insurance industry, as Chile is a well-established market that incurred significant damage to the highly insured commercial and industrial sectors of the country—the majority of which is reinsured abroad. Insured loss estimates tend to rise in the weeks and months following a significant earthquake, and the loss estimates following the Chile earthquake were no exception. For example, in April 2010, Munich Re estimated its burden of the industry insured losses at $700 million, revising this estimate upward to $1 billion in June 2010. Swiss Re issued a pre-tax loss estimate of $500 million in March 2010 and increased this estimate to $630 million in June 2010. Approximately 90% of the insurance coverage in Chile is ceded to the global reinsurance market. Total losses estimated by La Asociación de Aseguradores de Chile (AACh), the insurance association in Chile, escalated over time as well. On March 2, industry losses were estimated between $2.5 billion and $2.6 billion, rising to $4 billion on March 5, and finally ranging between $5 billion and $8 billion in September 2010.

The rising estimated losses over time are a function of both the uncertainty of modeling the loss in the immediate aftermath of the event and the time needed to gather detailed claim information and make payments. For example, the Chilean insurance and securities regulator (SVS or Superintendencia de

Line of business	*Number of claims*	*Amount (in $ millions)*
Residential	*189,451*	*$1,256*
Automobile	*4,678*	*$22*
Commercial (insured amount up to $55 million)	*24,276*	*$1,334*
Large risks (mostly industrial: insured amount over $55 million)	*2,840*	*$1,423*
Total	***221,245***	***$4,035***

Insurance claims and amounts paid, as of December 2010; total estimated loss is expected to reach $8.5 billion (Source: Ríos, 2011)

Valores y Seguros de Chile) placed a 90-day limit on the filing of earthquake-related claims for residential damage; however, settling these claims takes much longer. At the end of March, less than 20% of claims had been paid. On April 30, 2010, $249 million in claims were paid; by the end of May, this payout rose to $383 million and by September, insurers paid $640 million in claims on over 105,000 damaged properties. The majority of these claims were associated with properties with mortgages, as the take-up rate for earthquake insurance is much higher for mortgage-based properties compared to residences without a mortgage (e.g., as banks require earthquake insurance coverage as a loan prerequisite).

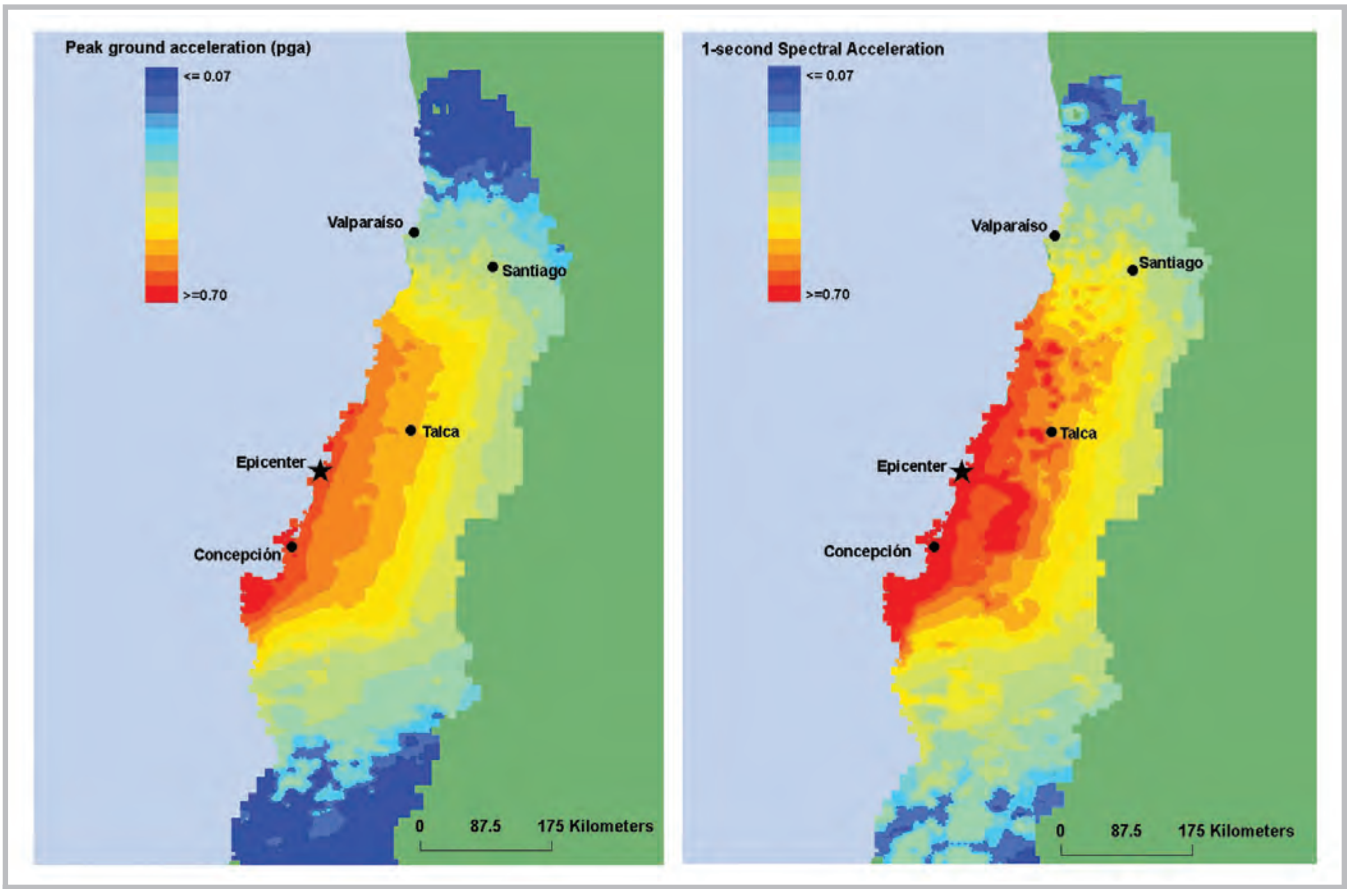
In April 2011, the SVS estimated that final insured losses reached $8.5 billion (Ríos, 2011). Claims reached 221,000, with close to 190,000 in residential (housing) claims. However, as of December 2010, the total amount of outstanding claim payments is dominated by payments on commercial and industrial risks. As expected, large industrial claims are still in the claims adjustment process due to the difficulty in estimating business interruption (BI) losses.

9.3 Modeling Insights

In mid-March 2010, RMS issued a direct property loss estimate of between $30 billion and $40 billion from the 2010 Maule, Chile Earthquake. This estimate covered losses to residential, commercial, and industrial properties at risk (excluding infrastructure and lifeline damage), including BI loss and the escalation of losses due to post-event complications, such as the lack of materials and workers to rebuild (i.e., demand surge). Approximately 75% of estimated losses were sustained in the Biobío and Maule regions, with the majority of the remaining losses in the more northern Santiago and Valparaíso regions.

This estimate was developed using the RMS® Chile Earthquake Model, wherein the recurrence rates for large events are based on a time dependent recurrence model. As of 2010, the return period for a M8.8 or greater event is approximately 120 years, according to the RMS model. From a loss perspective (i.e., considering the estimated economic losses between $30 and $40 billion), the return period is between 65 and 95 years.

To determine an estimate of the property damage from this event, RMS utilized its database of property values that covers residential, commercial, and



Ground motion footprint of the 2010 Maule, Chile Earthquake, as modeled by RMS; estimates of peak ground acceleration (pga) (left) and 1-second spectral acceleration (Sa) (right) illustrate the differences in ground motion footprints. Peak ground acceleration is a good index for estimating damage to shorter buildings, while 1-second spectral acceleration is a good index for estimating damage to taller buildings.

industrial exposures. This property exposure, for example, included reinforced concrete buildings in the metropolitan areas surrounding Santiago, Concepción, and Valparaíso, unreinforced masonry buildings in low-income and historic areas, and industrial complexes in Talcahuano and Coronel. This exposure was analyzed using a ground motion footprint developed by RMS and the vulnerability of the Chilean building stock, as captured in the RMS® Chile Earthquake Model. Data from the RMS reconnaissance team who arrived in Chile on March 5, 2010, verified the assumptions in ground motion and vulnerability, and in some cases, damage observations were used to adjust the modeled loss. For example, on its first day in the field, the RMS team observed no signs of structural damage in modern high-rise buildings within the central business district of Santiago; losses within this region were adjusted accordingly. The reconnaissance effort also provided key insights into the uncertainties associated with this event.

There was enormous uncertainty in estimating losses for Chile in the immediate aftermath of the event. Modeling uncertainty was a function of:

- The poorly constrained ground motion estimates provided by the USGS;
- The number of high-rise buildings in the regions of Santiago, Viña del Mar, and Valparaíso that would require significant repair work or need to be demolished;
- The time to inspect, and replace if needed, large industrial equipment damage; and
- The impact of infrastructure damage on the economy's ability to recover.

In the weeks following the event, RMS provided guidance on these key drivers of uncertainty. Moreover, the status of significant commercial properties, and the recovery of industrial facilities and infrastructure have been summarized in this report. In this section, additional modeling insights are summarized, including fire following earthquake and loss amplification.

9.3.1 Fire Following Earthquake

It is estimated that losses due to fire following the event, excluding those intentionally set by looters (e.g., in Concepción), were responsible for less than 5% of the total insured loss and a very small fraction of the total economic loss. While fires caused by the earthquake did not contribute significantly to total losses, RMS reconnaissance teams observed a few cases of major fire loss. For example, a large latex factory in Colina, a chemistry building at the University of Concepción (Universidad de Concepción), industrial facilities near

Grocery store in Coronel, Chile, destroyed by fire following the 2010 Maule, Chile Earthquake (Source: RMS)

Santiago, including a plastics factory and a textile warehouse, and a distribution warehouse near Chillán were all engulfed by flames and sustained complete losses. Video footage on the Internet shows fires at these locations just minutes after the earthquake. Moreover, images captured from the International Space Station approximately seven hours after the earthquake showed smoke plumes at the University of Concepción, among other locations within the city. In addition to these high-value locations, smaller fires were observed in homes, apartment buildings, and small businesses throughout the affected region.

9.3.2 Loss Amplification

At loss ratios of the magnitude experienced in Chile (i.e., a total economic impact representing 17% of Chile's GDP), loss amplification typically increases the cost of goods and labor, particularly in areas with little access to alternative sources. In the first three weeks following the event, higher prices were observed in products ranging from fruits and vegetables to pharmaceutical drugs and construction materials. The government enforced regulations to prevent price

Long lines and military guards in front of the Sodimac construction supply store in Concepción gouging for some types of goods, but many consumer items were limited in supply and highly demanded.

Popular construction materials, particularly zinc and iron derivatives such as nails, roofing material, and steel reinforcing bars, were in short supply. This was partly a result of halted operations at the CAP steel manufacturing plants and furnace damage at a Gerdau Aza steel manufacturing plant. Supplies were also limited because of damage to major highways and ports. Weeks after the event, a sheet of metal roofing cost 40% more in some areas than it did before the earthquake. Similarly, the price of roofing nails had doubled. Major stores that supplied these materials, such as Sodimac, rationed purchase quantities.

The global prices of exported goods, such as copper, pulp, and cement, increased as well, either due to halted production within Chile or speculation that the Chilean supply would be suspended. For example, copper prices jumped by approximately 5% following the event and pulp prices increased in many countries around the world, as the production in Chile's mills were disrupted. After several major cement plants in Chile suspended operations, the stock price of a major Peruvian cement company increased by over 100%. In the aftermath of the event, many industries began importing goods in an effort to augment the limited local supplies. Large quantities of cement were imported to supply the tremendous construction efforts associated with rebuilding civil infrastructure in Chile.

There was some concern about the Chilean economy in the months following the earthquake. Based on the available data, economic demand surge began to subside in Chile by the fall of 2010. The earthquake occurred just as Chile was emerging from an economic slowdown, with the GDP contracting by 1.7% in 2009. However, the annual GDP growth measured 5.2% in 2010. In mid-2011, the country's economy has rebounded.

9.4 Event in Perspective

While the 2010 Maule, Chile Earthquake was not an unexpected event, it has considerable implications for the global earthquake engineering research community. The event has shifted the landscape of hazard along the Chilean coastline, providing data for further study into aftershock sequences following large events. It has also created an opportunity to improve the seismic design requirements in the U.S. building code, based on observed damage and comparisons to the Chilean building code.

As a result of the 2010 earthquake, the time-dependent probabilities on the subduction zone have changed. In 2011, RMS updated its Chile Earthquake Model to reflect this change, adjusting the event rates to account for the occurrence of the M8.8 earthquake and the low probability of it repeating again in the near future. Also in 2011, the structural engineering research community continues to investigate the lessons learned for the construction of mid-rise and high-rise reinforced concrete buildings.

The event has additionally highlighted the importance of managing insured exposures in highly seismic regions, and how the public and private sectors can work together to rebuild following a devastating event. Particularly since the occurrence of the Christchurch, New Zealand Earthquake (on February 22, 2011) and the Tohoku, Japan Earthquake (on March 11, 2011), the need to prepare for future earthquake events is of paramount importance in high risk regions—as effective preparedness will reduce the risk of losses. ■

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