M8.8 MAULE EARTHQUAKE
February 27, 2010

MRP Engineering Summary Report **March 2011**

On February 27, 2010, a devastating M8.8 earthquake struck off the central coast of Chile, 105 kilometers north of Concepción, the second largest city in Chile. The earthquake occurred at a depth of 35 kilometers along the subduction zone where the Nazca plate under the Pacific Ocean slopes eastward and downward beneath the South American continent. The rupture zone extended almost 500 kilometers parallel to the Chilean coast, triggering a tsunami along the fault rupture area. Strong ground shaking lasted for over two minutes and caused structural damage to modern structures in Santiago (more than 300 kilometers from the epicenter). Over 16 aftershocks of magnitude 6.0 or greater followed the main event, including a M6.9 aftershock on March 11, 2010. The earthquake and tsunami were responsible for more than 500 deaths and destroyed half a million homes. MRP Engineering visited Chile several times in 2010 to document earthquake impacts, extent of damage, and recovery efforts. This report summarizes our observations.

SANTIAGO, CHILE

The capital city (with a population of over three million) is located more than 300 kilometers from the earthquake epicenter. Significant ground shaking lasted about 40 seconds and affected modern structures, highway bridges, historically significant buildings, and other critical facilities (airport, hospitals, etc.) as depicted in the images below. The ground motions levels approached design forces. The Chilean building code is comparable to mid-1990s US standards; however, the current Chilean reinforced concrete construction requirements include some significant differences.

Example of extensive structural damage at Ciudad Empresarial (Santiago area). This recent vintage five-story office building suffered extensive damage (see detail). Irregular layout and weak soils contributed to the damage.

Precast reinforced concrete construction at Ciudad Empresarial. Inadequate wall panel connections resulted in building damage.

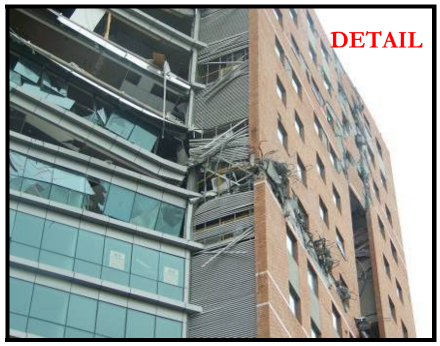
Modern high-rise residential tower in Santiago with extensive reinforced shear wall damage, as shown on the close-up photo. This building could not be occupied for months.

Collapsed reinforced concrete apartment building in Maipu area (Santiago). The structure featured tuck-under (open) parking at base.

CONCEPCIÓN AREA, CHILE

The city center is located on the east bank of the Bío Bío River just south of its outlet into the Pacific Ocean. Significant high-rise development (15- to 20-story office and residential towers) has occurred within the last few years and altered the city skyline. Major industries (petro-chemical, chemical, cement, steel, and fishing) are located just north of Concepción near Talcahuano. The region is also home to forestry products facilities. The earthquake impacts were significant and included:

- Structural and contents damage to modern buildings
- Damage to bridges crossing Bío Bío River due to soil failures
- Infrastructure and structural damage at industrial facilities resulting in significant business interruption



A number of high-rise buildings in Concepción suffered extensive structural damage as shown in the close-up photo on right.

Collapsed concrete tilt-up wall panels due to weak wall-to-roof connections.

Juan Pablo II (Concepción) bridge damage and riverbank lateral spreading.

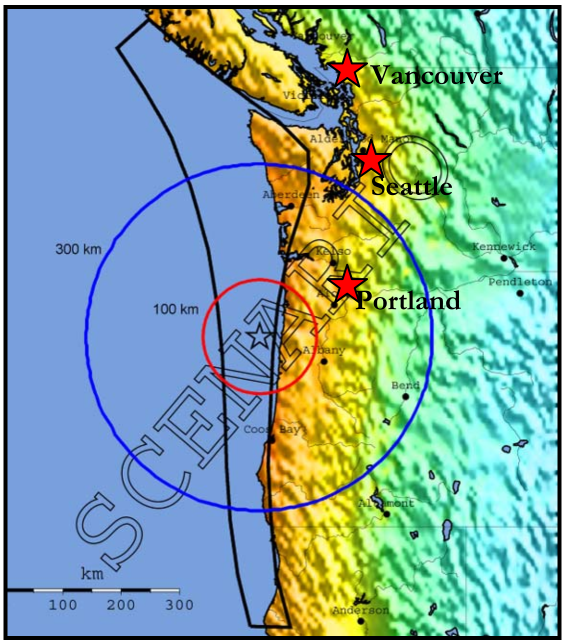
Collapsed thin-walled steel grain tanks.

Example of tsunami effects on the Talcahuano fishing fleet.

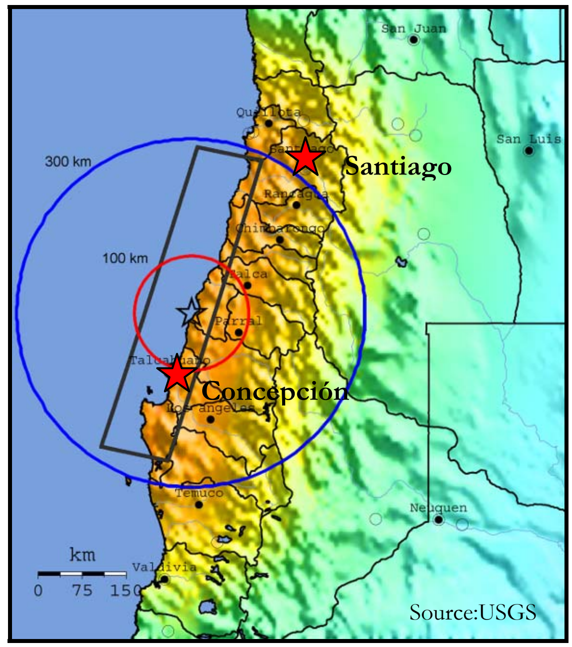
Panoramic view of heavy industry in Talcahuano.

SUBDUCTION ZONE EARTHQUAKES COMPARED

The 2010 M8.8 Chile and the 2011 M9.0 Japan subduction earthquakes are particularly relevant to the Pacific Northwest. This region is also located along the boundary of two tectonic plates, a geological structure known as the Cascadia Subduction Zone. One of the tectonic plates, the Juan De Fuca plate, forms the ocean floor, slides beneath (subducts) the North American plate, and is slowly driven into the earth's mantle. This seismic source is considered capable of generating M9 events every 300 to 500 years, with long duration ground shaking, multiple aftershocks, and tsunamis. The most recent event on this source occurred in 1700. In addition to affecting Pacific Northwest coastal communities, a M9 subduction zone earthquake would impact the metropolitan areas of Portland and Seattle, as well as Vancouver, British Columbia.



M9.0 Cascadia Subduction Zone scenario

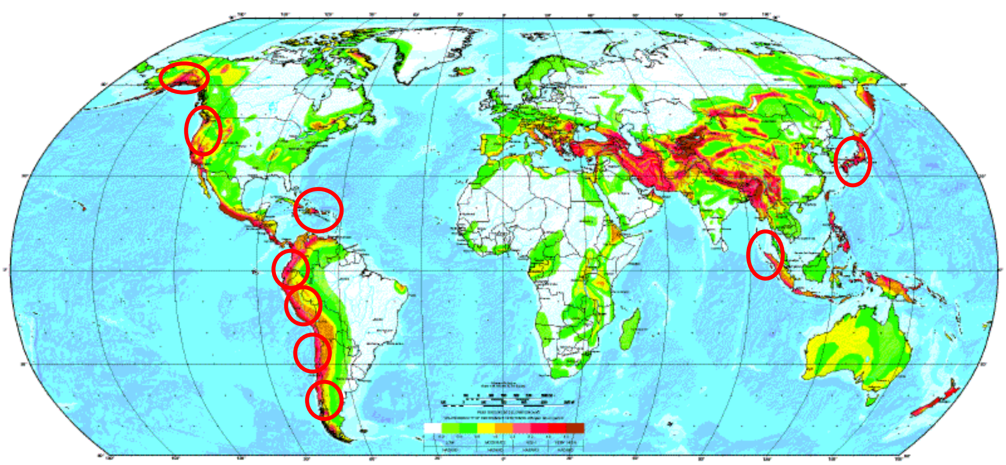


M8.8 Offshore Maule, Chile earthquake

Stronger shaking →

GLOBAL SEISMIC HAZARD MAP

The map at right provides ground-shaking levels for a 475-year earthquake level. Areas in dark red indicate the highest potential seismic hazard (ground shaking). Effects of local soil conditions are not included. Circled areas indicate potential zones of M8+ subduction mega-earthquakes.



Source: http://www.seismo.ethz.ch/gshap/

SANTIAGO—JUNE 2010 IMAGES:

Collapsed bridge repairs (Vespucio Norte Highway)

Destroyed modern industrial facility (Lampa)

Repairs at a production plant (Lampa)

Office building repairs (Ciudad Empresarial)

The M8.8 subduction earthquake of February 27, 2010 that affected central Chile and the capital of Santiago offers highly relevant lessons to other nations (including the United States and Canada) with modern urban areas located in seismically active regions. MRP Engineering visited Santiago following the earthquake to investigate the damage and in June 2010 to observe the post-event recovery. Our findings indicate that:

- Subduction type earthquakes can impact relatively distant population centers. Modern buildings in metropolitan Santiago (population 5.5 million and 300+ kilometers from the epicenter) experienced significant structural damage, leading to prolonged loss of use and expensive repairs.
- Damage to reinforced concrete buildings was related to structural wall discontinuities (tuck-under parking, irregular building geometry, at-grade wall offsets) and limited reinforcement at structural wall boundaries.
- Soil response (liquefaction, settlement, and ground shaking amplification) strongly influenced seismic performance of buildings, bridges, and buried utilities.
- The long duration of strong ground shaking caused damage to nonstructural components (exterior cladding, partitions, suspended ceilings, and contents) in buildings with relatively limited structural damage.
- In the days and weeks following the event, industry recovery was hampered by damage to external infrastructure (electricity, water, and transportation), damaged internal utilities, or business interruption due to "supply-chain" issues.
- As exemplified by the accompanying photos from June 2010, rebuilding and recovery from mega-events, such as subduction zone earthquakes, may take many months to complete, resulting in significant downtime and loss-of-occupancy for damaged facilities.

These observations suggest that organizations with significant operations in earthquake-prone regions should consider proactive steps to understand their risks and address unacceptable exposures before the next earthquake. The following sections discuss earthquake hazards and approaches to managing seismic risks.

RECOVERY FROM MEGA EARTHQUAKES

The M8.8 Maule earthquake of February 2010 impacted much of central Chile and resulted in over US$30 billion in economic losses. MRP Engineering returned to Chile (Concepción area) in December 2010 to observe successes and challenges in rebuilding the region. As discussed in the following paragraphs, although nearly a year has passed since the mega-earthquake, this event continues to provide valuable insight on recovery and reconstruction issues.

December 2010: Construction is in progress on a new highway bridge over the Bío Bío River in Concepción. This crossing will replace a bridge damaged by the earthquake. The city skyline (background) includes a number of vacant residential towers.

Concepción, Chile's second largest city, is located about 100 kilometers south of the earthquake epicenter. The region's built environment experienced significant damage due to ground shaking (lasting over a minute), soil failures (liquefaction), and tsunamis. Many modern high-rise residential and office buildings sustained major structural damage in the February event. Some of these structures remain vacant.

Concepción City Center: Collapsed grain bins have been removed but not yet replaced as shown in these two images taken in March and December of 2010. The 20-story residential tower in the background remains vacant. The right photograph includes the toppled Rio Alto tower (circled) which is still under investigation.

The region is home to important industries such as: fishing, shipping (ports), power generation, petroleum refining, and forest products. Some waterfront operations suffered extensive damage due to soil liquefaction and tsunami. Further inland, there are examples of relatively modern plants that sustained limited structural damage, but incurred significant business interruption losses due to damaged critical plant equipment or utilities (transformers, cooling towers, or turbines). Before returning to service, many such components or systems require post-event inspections and testing. Repair or replacement of specialized parts may take months to complete.

Most of Chile's central coast communities were affected by tsunamis that followed the February earthquake. In Talcahuano, a bayside community located directly north of Concepción, town center buildings housing important municipal and community operations were still in the midst of cleanup and repair from water and ground-shaking damage. Many streets were blocked off for reconstruction of pavement and underground utilities, as pre-Christmas street commerce was attempting to cope at the time of our visit. A new school (replacing a damaged and flooded waterfront campus) was due to open on an elevated site, just in time for the new school year which begins in March in Chile. Before the earthquake, Isla Rocuant's industrial zone housed an enclave of thriving fish processing plants. In December, post-tsunami cleanup continued and only a few plants were operating. The local fishing fleet looked depleted. On the other hand, the container shipping business at the nearby port of San Vicente appeared to have recovered.

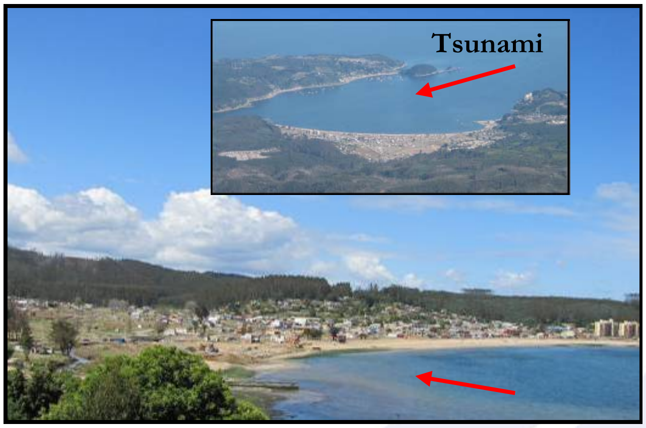
Street and utility reconstruction in Talcahuano city center is evident throughout the low-lying areas of this community.

Tsunami-prone areas of Port of Coronel (south of Concepción) are surrounded by new flood walls.

San Vicente Bay's industrial zone is recovering. A fish-processing plant (circled) has been demolished. Beach area was contaminated due to broken petroleum lines.

Damaged condominium tower in San Pedro still stands vacant. Corner balconies remain shored up.

Further north along the coast lies Dichato, a beachfront community that once bustled with lively restaurants and shops along its crescent-shaped beach. Today, the waterfront feels like a ghost town. The devastation is reminiscent of coastal communities in the United States following Hurricane Katrina in 2005. It will be years before communities like Dichato will find their new future. Meanwhile, the displaced residents hang on. Some live in sterile fast-track or temporary housing that lacks the former appeal.



Panoramic view of the Dichato waterfront community devastated by the tsunamis that followed the earthquake

Fast-track community of wood-framed housing for residents displaced by tsunamis

Bío Bío River (Chile's longest) bisects Chile as it flows from the Andes and empties into the Pacific Ocean near Concepción. Functioning river crossings (highway and rail) are of vital regional economic importance. The reconstruction of Concepción's highway bridges represents one of the success stories in the aftermath of the February earthquake. The Juan Pablo II Bridge, a two-kilometer-long four-lane highway crossing, sustained major damage to its foundations and columns due to soil liquefaction. This bridge was re-opened to traffic in October. Regional transportation system repairs are evident throughout the area as work continues on stabilizing bridge embankments and slopes along roadways.

Juan Pablo II Bridge damaged in the Fabruary earthquake was restored to service in October 2010.
This photo from March 2010 illustrates some of the bridge foundation damage as evidenced by the sagging roadway.

The photo on the left shows Juan Pablo II Bridge fractured column caused by soil liquefaction and lateral spreading along the the Bío Bío riverbank. The photo on the right depicts the new bridge girder and columns.

SUBDUCTION EARTHQUAKE IMPLICATIONS

Chile is making headway in rebuilding its heartland following a massive subduction zone earthquake that affected modern structures as far away as Santiago (335 kilometers from the epicenter). However, the recovery from a major earthquake need not be a lengthy process. Organizations with earthquake exposures can learn from this event and should consider proactive steps to enhance safety, reduce damage, and minimize downtime.

- Review business recovery plans to include dedicated resources (contactors, suppliers, and engineers).
- For existing operations, assess earthquake risks (buildings, contents, critical lifelines, suppliers of critical parts) and identify specific areas of improvement relative to safety and business risks.
- For proposed construction, perform independent design reviews to verify the desired seismic performance. Building codes tend to focus on occupant safety rather than limiting damage in a major earthquake.
- Verify seismic restraint of equipment and contents. This is a cost-effective method of loss control.

MRP ENGINEERING SERVICES

MRP Engineering is a structural engineering and risk analysis firm (based in metropolitan Seattle, Washington) and provides proactive risk analysis for natural hazards, damage investigation, and upgrade design. We assist clients to protect their business operations from risks to physical assets resulting from extreme events such as earthquakes and hurricanes. Our philosophy is to listen to your needs and then provide you with practical and cost-effective structural engineering-based risk reduction solutions. Services include:

- Earthquake and wind risk evaluation
- Structural benefit-cost analysis
- Upgrade design
- Independent design review
- Damage (root cause) investigation
- Expert witness and claim support