

POST-DISASTER SURVEY FINDINGS FROM THE M8.8 CHILE EARTHQUAKE

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EDITOR'S NOTE: In the early hours of February 27, 2010, a massive earthquake struck off the coast of Chile. The magnitude 8.8 jolt displaced the entire city of Concepción at least 3 meters to the west and moved Buenos Aires—1200 km from the epicenter—an entire inch. In the days following the quake, AIR's post-disaster survey teams visited affected areas in Chile. The team was comprised of AIR Principal Engineers Dr. Guillermo Franco and Dr. Tao Lai, and AIR Senior Research Engineer, Guillermo Leiva. Dr. Franco also served as member of the Earthquake Engineering Research Institute (EERI) team. This article presents the AIR team's preliminary findings.

By Dr. Guillermo Franco, Guillermo Leiva and Dr. Tao Lai

INTRODUCTION

Early on the morning of February 27, off Chile's central coast, a rapid release of energy at one of the world's major subduction zones resulted in a massive temblor. Thousands of adobe buildings crumbled and modern cities—with state-of-the-art structures adhering to advanced building codes—were tested by about 120 seconds of strong ground shaking. A tsunami followed within thirty minutes.

The M8.8 earthquake that struck Chile that day was the world's fifth largest since instrumental record keeping began. Not even those buildings constructed according to some of the most stringent codes in the world could survive unscathed; several modern high-rise structures collapsed or suffered severe structural damage. Sources, including the Chilean Red Cross, have estimated that the Maule earthquake—named after Chile's Maule Region—damaged more than 500,000 homes. The event also severely impacted Chilean infrastructure, including roads, bridges, airports, utilities and telecommunications networks.

CHILE'S SEISMIC SETTING

Chile has a long history of earthquake activity. Since 1973, the country has experienced thirteen events of magnitude 7 or greater. The most well-known of these occurred fifty years ago this year, on May 22, 1960, and with a magnitude of 9.5; it was the largest quake ever recorded. The earthquake struck near Valdivia, some 900 km south of Santiago, and generated a great tsunami that caused widespread losses and affected several countries bordering the Pacific Basin.

Chile's seismicity is a consequence of the strong, dynamic tectonic processes that characterize the so-called "Pacific Ring of Fire," on which Chile is located. The Pacific Ring of Fire is a nearly continuous series of plate boundaries that enclose most of the Pacific Ocean. Chile sits on the South American plate and its coastline marks the limit between the South American plate and the subducting Nazca plate.

The Nazca and South American plates converge at a rate of about 80 mm per year. Inter-locking between the plates

sometimes occurs. Over time, it can cause the accumulation of great stresses. When the rock material can no longer sustain an increase in stress, a sudden slip may take place, producing an earthquake. On February 27, in less than 3 minutes, the Nazca plate subducted under the South American plate by several—up to 14—meters. The length of the rupture has been estimated at about 450 km.

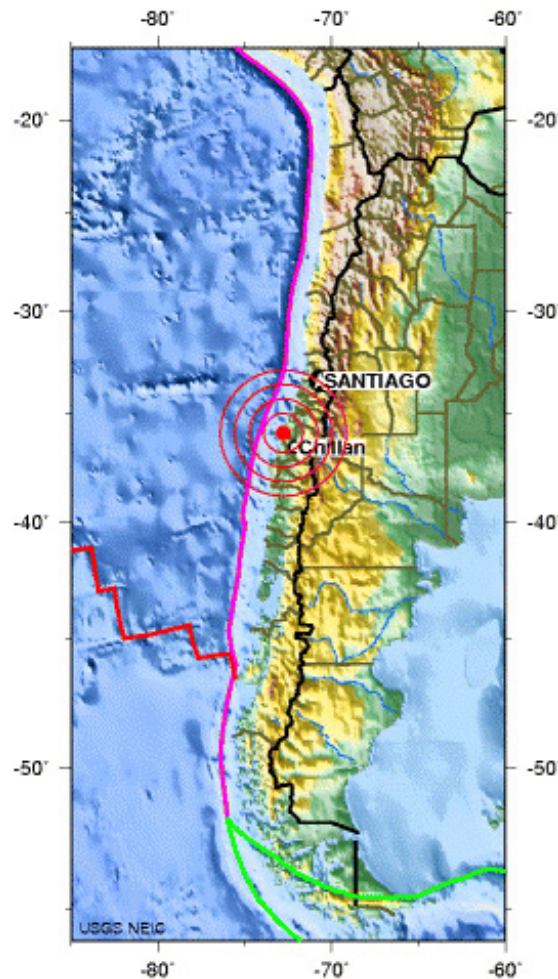


Figure 1: Epicenter of the February 27 Maule earthquake. (Source: USGS)

Prior to the Maule earthquake, research on strain rates and plate motion along this stretch of the subduction zone suggested the presence of a mature seismic gap, based in large part on the absence of an earthquake exceeding M8 there since 1835. In a 2009 article¹, Ruegg et al. estimated the potential for an earthquake between magnitude 8 and 8.5 in the Concepción-Constitución area in the near future. The campaign of measurements on which the research was based spanned several years. However, the publication of the paper could not have been more timely.

CHILE'S BUILDING CODE HISTORY

Chile's first official building code was implemented in the 1930s, prompted by lessons learned after the M7.6 Talca earthquake in 1928. As happens in countries worldwide, revisions to Chile's building code occurred throughout the twentieth century as destructive earthquakes provided opportunities to detect flaws in existing techniques and to suggest improvements to building design provisions.

In 1939, a M8.3 earthquake struck the south of the country, causing 30,000 deaths and motivating the government to appoint a new committee to study earthquake impacts. The results of that study led to a major code update in 1949.

In 1958, a low-magnitude crustal earthquake near Santiago caused unexpected damage due to the particular frequency content in the ground motion signal, which differed from typical subduction earthquakes. Insights from this event led to a revision of building regulations. The revision was finally approved in 1972, benefitting from the additional lessons learned after the 1960 M9.5 Valdivia earthquake.



Figure 2. Chile's modern building code was updated three times in the 20th Century (Source: AIR).

Another revision came as a result of the M7.8 Valparaiso (Santiago) earthquake of 1985, which collapsed 66,000 houses and damaged another 127,000. The new code—in use today—was implemented in 1993, with some modifications in 1996.

Most reinforcement detailing considerations were adopted from the American Concrete Institute norms. However, important provisions for steel confinement in shear walls (boundary elements) are still missing in the Chilean code, as evidenced by damage patterns observed in February's Maule earthquake.

Since the implementation of the most recent building code, more elaborate architecture has sprung up in Chile's cities. Simultaneously, the pressure is on to reduce construction costs and maximize floor area. Often, the result is irregularly shaped buildings with fewer and more slender shear walls.

In fact, the amount of wall per volume of building has decreased in recent decades and typical wall thickness has dropped from 30 cm in the 1980s to about 15 cm today.

OBSERVATIONS FROM AIR'S POST-DISASTER DAMAGE SURVEY

AIR engineers were on site in various regions of central and southern Chile beginning Friday, March 12. In addition to observing damage and building performance in the towns and cities shown in Figure 3, AIR's team conducted interviews with industry experts, local engineers, and governmental and humanitarian organizations. The goal was to obtain a detailed picture of the severity and geographic distribution of the damage.

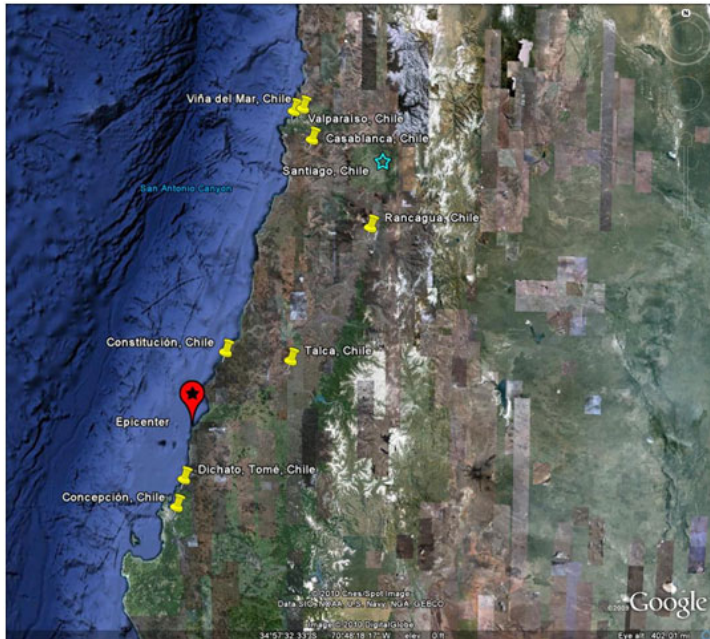


Figure 3. Cities visited during AIR's damage survey. (Source: Google Earth).

Overall, Chile's building stock performed well. Only one modern reinforced concrete building in Chile suffered a complete collapse, and perhaps 100 other modern engineered buildings will have to be demolished due to severe damage. However, the most significant damage was to older adobe structures, which are widespread in the Maule region and are characterized by poor seismic performance. In some cases where the earthquake did not cause problems, the tsunami did.

The paragraphs below highlight incidences and issues of damage. Ultimately, the information collected will assist AIR in the process of model validation and provide insight

into potential model enhancements. To date, damage surveys are still an important resource for research in the catastrophe modeling field.

OBSERVATIONS

Talca, the capital of the Maule Region, and some 115 km from the epicenter, was one of the towns hardest hit. Its historical center, which consisted predominantly of adobe, was devastated. Approximately 1,500 adobe homes in Talca were either destroyed or were undergoing demolition at the time of AIR's survey. The municipality has not yet fully defined a plan for reconstruction, to the consternation of residents.



Figure 4. Demolition crews have begun their work in Talca. (Source: AIR).

In Concepción, the largest city near the quake's epicenter, several high-rise structures will have to be demolished. According to the city's municipality, a total of eight buildings are scheduled to be torn down, while an additional 48 require an in-depth inspection to assess whether they can be repaired.

One building in Concepción scheduled for demolition is the Torre O'Higgins building, a reinforced concrete high-rise of 21 stories. Figure 5 shows the multiple shear failures along its height, as well as the failure of what appears to be a dual system of frames and shear walls. This building has vertical irregularities that may have been responsible for its poor performance. Preliminary observations by various structural engineering teams, including AIR's survey team, conclude that these irregularities are likely to have increased the torsion of the building under earthquake loads, which led to severe damage.



Figure 5. The Torre O'Higgins high-rise suffered severe damage and is scheduled for demolition. (Source: AIR).

The only fully collapsed modern building in Chile—a multi-story reinforced concrete residential structure—was on Avenida Arturo Prat in Concepción (Figure 6). The building crumbled a few minutes after the earthquake struck, killing eleven people. Initial observations into what caused the collapse indicate insufficient reinforcement, vertical discontinuity of shear walls, and possibly poor material quality.



Figure 6. The only fully collapsed modern building was located in Concepción. (Source: AIR).

North of Concepción, and 74 kilometers northeast of the earthquake's epicenter, the town of Constitución sits on a coastal plain surrounded by hills. When the earthquake struck, old and fragile construction in Constitución was heavily damaged. The subsequent tsunami caused even more destruction.

Figure 7 shows a section of the city in the quadrant defined by Hospital, Oñederra, Rengifo, and Echeverría streets. Most of the buildings on the plain will have to be demolished. Tourism in this seaside town has been brought to a halt, leaving even undamaged apartment buildings empty. Fisheries and industry in the town have also been paralyzed.



Figure 7. Constitución is on a plain surrounded by hills. While the hills were not greatly affected by the earthquake, structures on the plain were heavily damaged due to shaking and tsunami. (Source: AIR)

Damage on February 27th was not limited to that from the earthquake; AIR's engineers also observed havoc wreaked by the tsunami, which was, in some locations, far more deadly than its seismic precursor. The tsunami impacted about 950 kilometers altogether, from Valdivia, north to regions of the coast just south of Valparaíso. In the coastal towns AIR visited, three tsunami waves had struck. Many informal wood homes in the Maule Region were built directly in flood zones, and consequently, many were completely washed away.

In Santiago, AIR's survey team visited La Ciudad Empresarial—a business park just outside the capital, some 325 km from the epicenter. The park is home to multinational corporations and hotels. Unlike the isolated

structural damage observed in other locations the team visited, structural damage here spanned the entire north-west corner of the park. The most significant damage was to modern mid- and high-rise buildings.

AIR's team preliminarily concluded that damage in this area might have been exacerbated by soft soils, probably highly saturated with water, that characterize the basin (Figure 8). The area had been a combination of wetlands and farmland until construction on the park began about twenty years ago. The incoming seismic waves from the February 27 event were likely trapped by the basin and amplified by the soft alluvial soils, which in turn intensified damage to structures. Note that the buildings in the foreground of Figure 8 suffered no damage at all since they were sitting on stiffer ground on hills at the basin's edge. Figure 9 shows further instances of ground failure at La Ciudad Empresarial.



Figure 8. Panoramic view of La Ciudad Empresarial, Huechuraba, Chile (Source: AIR)



Figure 9. Settlement (left) was observed outside buildings in La Ciudad Empresarial. Cracks (right) propagated along the ground due to soil settlement. (Source: AIR).

Chile's construction largely relies on shear wall engineering. Much of it performed well, but there were exceptions. In the coastal city of Viña del Mar, just north of Valparaiso, AIR engineers entered the building pictured below, which had suffered a partial collapse of a concrete shear wall. Two of the building's structural walls failed, causing a 10 centimeter vertical displacement. The whole wall segment pictured in Figure 10 exhibited severe tilt.



Figure 10. Partial collapse of high-rise apartment building in Viña del Mar. (Source: AIR)

Inside the building, the team noticed severe cracking in the walls of an apartment unit they examined, as well as deformation of the slab and cracking of the stairwell. Figure 11 shows the interior side of one of the building's structural walls; compression due to the effect of gravity loads compounded by the bending of the structural system might have caused the failure of this wall section and the subsequent buckling of the longitudinal rebar.



Figure 11. Buckled longitudinal rebar in structural wall of Viña del Mar building (Source: AIR).

In Maipú, a municipality south-west of downtown Santiago, AIR's team visited a building that was partially collapsed due to shear wall failure; it will have to be demolished (Figure 12, right). The building appeared to have suffered excessive lateral displacement and, as a result, it lost support from the load bearing walls in one of its corners (Figure 12, left).



Figure 12. Partially collapsed building in Maipú, greater Santiago. (Source: AIR)

Pounding is the technical term for the collision of adjacent buildings during an earthquake due to insufficient lateral clearance or to a poorly designed construction joint. This type of effect was observed in one apartment building in Independencia, which consisted of two L-shaped structures symmetrically arranged and built within a year of each other. The construction joint was not adequately designed to provide enough separation to prevent pounding and, as a result, cracks were evident at the location of the joint (Figure 13).

The possible torsion incurred by the two L-shaped structures during the shaking might also have exacerbated the disconnection of the building's stair slabs, which the team observed in the building's interior stairwells.² Despite this and other damage, the building has been deemed habitable by inspection agencies.

The wall structures of the Central Park building on Balmaceda Street in Santiago experienced dramatic failures. Local residents reported that the major lateral shaking from the earthquake took place in the direction perpendicular to the façade (Figure 14), which is the weakest direction of the building in terms of overall resistance.

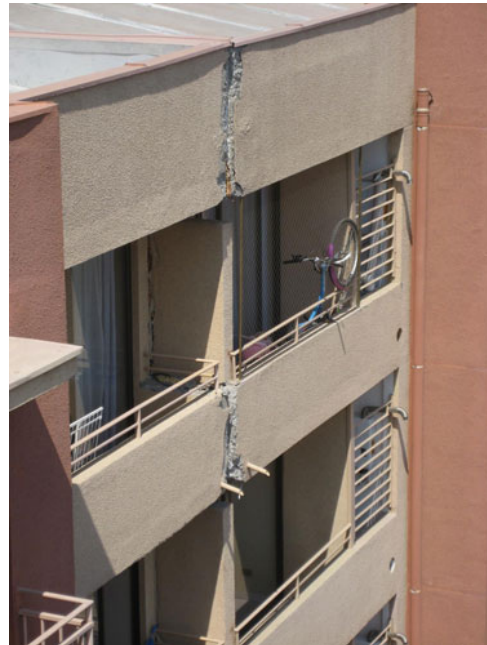


Figure 13. Evidence of pounding between the original structure and a later addition. The construction joint did not provide enough separation to prevent pounding. (Source: AIR)

A neighboring building (in the far left background)—apparently with similar structural characteristics but rotated by 90 degrees—showed no damage. This suggests that the strongest lateral motion took place coincident with the first building's weakest direction and the second building's strongest direction. These buildings provided a clear illustration of how the orientation of a building with respect to the ground motion it experiences can affect its performance.

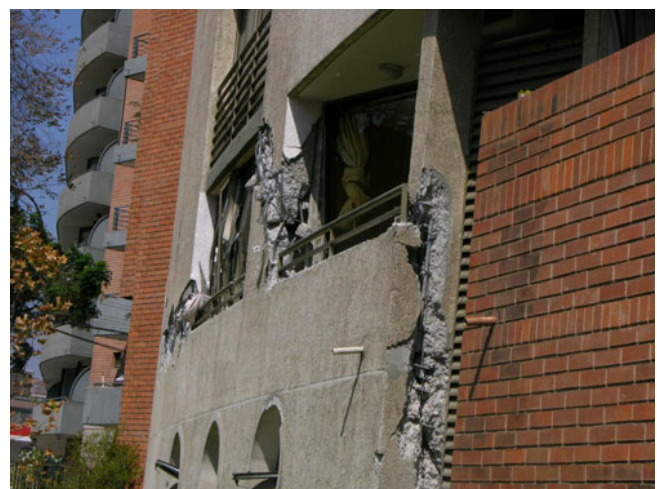


Figure 14. Failure of structural wall, Central Park building. (Source: AIR)

INSURANCE AND SOCIAL IMPACTS

The experience of the tenants of the Central Park Building (figure 15) gave AIR's team an opportunity to better understand the social ramifications of insurance tools. The building consisted of 150 units. Approximately half had been purchased with cash, a common savings strategy in Chile; having paid for their properties in full, these families did not have mortgages. Residents of the other half of the units had purchased them through bank mortgages, which require compulsory insurance. As a result, half of the owners had earthquake insurance and half did not.

Those who had insurance were actively advocating for the demolition of the building and the recovery of their assets. However, those without insurance opposed this solution since it would mean that they would lose much if not all of their savings. The situation highlights the need for affordable and accessible insurance solutions; with such solutions, communities—and indeed economies—could recover more quickly from events like the Maule earthquake. Cat pools and other mechanisms may offer reasonable alternatives for this kind of socially responsible coverage.

In some cases, new technology may mean that damaged buildings need not be demolished. There are already new businesses that promise to introduce a large diameter column that is claimed to be able to correct the existing tilts and resist the structural loads. Whether such efforts will succeed remains to be seen. Ultimately, the outcome will impact insured losses, but exactly what the impact will be is not clear at this time.

CONCLUSIONS

Despite some dramatic instances of building failure, the overall story is one of success. In Santiago, where business was largely back to usual two weeks after the event, structural damage was largely confined to relatively small pockets within the city. Santiago's financial district—brimming with new, highly engineered high-rises—performed well. Almost no damage was observed, though conversations with employees revealed that there had been some damage to office contents and limited damage to non-structural elements.



Figure 15. Modern construction in Santiago's financial district (Source: AIR).

In very general terms, insured losses are expected to derive from the aforementioned large structural failures, from small to moderate claims in the buildings' reported damaged, infrastructure damages (some of which are insured), and business interruption losses due to the direct impact of the earthquake or due to indirect effects triggered by the failure of lifelines.

According to recent reports, demolition of code-compliant buildings of three stories or taller in Chile will be necessary for less than 1% of the 10,000 or so that were affected by the quake. Even so, the structural damage observed to many buildings, particularly bearing-wall concrete frames of 12- to 26-stories, suggests the existing code may have some weaknesses.

The current code does not require shear wall boundary element confinement.³ It is likely that damage would have been even further reduced had provisions for this been covered by the 1996 code. In any case, the 1996 code, which shares many traits with American regulations, has withstood an important test—limiting both property damage and lives lost.

As tragic as the Maule earthquake was for the people of Chile, earthquakes of this magnitude provide invaluable information for seismologists and engineers. Since the Chilean building code was based in some measure on the construction codes developed in the U.S., this event represents a large-scale case study for those code provisions. However, while the Chilean code adopted many of the standard recommendations from the American code, some clauses were deemed unnecessary for the Chilean territory based on previous historical experience. The Maule earthquake has clearly shown that the code was fundamentally sound—but it also shows that, had those additional recommendations been heeded, further damage would have been avoided.

In the end, the earthquake largely validated the collective wisdom reflected in advanced design practices and emphasizes the need to upgrade—and enforce—codes in other parts of the world.

1 J.C. RUEGG, ET AL., 2009. "INTERSEISMIC STRAIN ACCUMULATION MEASURED BY GPS IN THE SEISMIC GAP BETWEEN CONSTITUCIÓN AND CONCEPCIÓN IN CHILE", PHYSICS OF THE EARTH AND PLANETARY INTERIORS, 175 78–85.

2 DAMAGES TO STAIRWELLS WERE OBSERVED IN SEVERAL BUILDINGS IN VIÑA DEL MAR AND IN SOME NEIGHBORHOODS OF SANTIAGO.

3 BOUNDARY ELEMENT CONFINEMENT REFERS TO THE ADDITIONAL STEEL REQUIRED AT THE END OF A SHEAR WALL.

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