THE MAGNITUDE 8.8 OFFSHORE MAULE REGION
CHILE EARTHQUAKE OF FEBRUARY 27, 2010

PRELIMINARY SUMMARY OF DAMAGE
AND ENGINEERING RECOMMENDATIONS

A Report to the World Bank

by

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April 18, 2010
Cover: Torre O’Higgins office building in Concepción.
Back Cover: Constitución.
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However, we are most grateful to the Chileans who, in the middle of this difficult period, had the forbearance to graciously tolerate our team’s professional curiosity.
EXECUTIVE SUMMARY

Our team of structural and earthquake engineers investigated the effects and damage from the February 27, 2010 Chile earthquake and tsunami to: (1) observe first hand how new and old buildings and infrastructure performed; (2) study what needs to change in our design and construction practices as well as our building codes to reduce future damage and loss of life; and (3) evaluate what Chile can do to reduce to an acceptable level the remaining risks due to earthquakes and tsunami. We investigated much of the most affected region of Chile, including its three largest metropolitan areas (Santiago, Valparaiso/Viña del Mar and Concepción) and several other cities located in between. We also toured the coastal region south of Valparaiso to Constitución by air and Constitución itself by land.

This report is based on the professional experience of the authors, their field visits in Chile, and their discussions with many earthquake professionals working in the research and the practice of seismology and earthquake engineering. The assessments and recommendations are preliminary and need further analysis and development in order to substantiate a basis for policy decisions.

From an engineering perspective, this is the most important earthquake in modern earthquake history. With a magnitude ($M_w$) approaching 9, it is the first mega-earthquake to strike a modern city full of state-of-the-art structures, industries, and infrastructure. Chile has excellent structural and earthquake engineering. Additionally, it has a modern building code that is comparable to and often has exceeded those of California and Japan. All this was tested by an intense ground shaking that lasted about 120 seconds –compared to 40 and 20 seconds for the 1906 and 1989 San Francisco earthquakes, which had magnitudes of 7.9 and 6.9, respectively.

Thousands of buildings collapsed or were severely damaged. Most of these were older buildings built without an earthquake engineering design. These included important government buildings, hospitals, residential and commercial buildings, and industrial infrastructure. A few new high-rise buildings, including residential and commercial buildings, were damaged beyond repair. A handful of modern buildings totally or partially collapsed. Most buildings that were designed to resist earthquakes performed well. In contrast, the non-structural features of some new buildings performed poorly. Poorly performing features include decorative architectural details, suspended ceilings (locally called “american ceilings”), and poorly anchored or braced equipment.

In this report we summarize the performance of most classes of buildings and infrastructure. In addition, we make specific recommendations regarding: (1) further data that need to be collected and analyzed in order to understand what can be done to improve future performance and future codes; (2) the analyses that need to be conducted to evaluate the risks due to the action of earthquakes and tsunami in Chile; and (3) the earthquake risk-reduction projects that can be undertaken to eliminate or reduce future risks in Chile to acceptable levels.

The earthquake affected 82% of the country’s population. The final official casualty count includes 577 deaths. According to press reports at the time of this report’s preparation, the overall damage to infrastructure is estimated at 30 billion US dollars. If building interior damage and business interruptions were also included, we estimate that the overall economic loss would increase substantially, reaching 50 to 60 billion US dollars. This is a rough
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estimate by the authors, based on prior experience with similar estimates published by the press after numerous past earthquakes. Much of these losses could have been prevented with simple engineering details and good seismic risk management at a reasonable cost and time.

Based on our observations, we make recommendations throughout the text of this report, and we summarize some of these recommendations at the end as follows: (1) establish a national program for damage prevention and earthquake risk reduction; (2) establish and conduct specific programs for damage prevention and earthquake risk reduction; (3) revise and improve the Chilean seismic code; (4) create and conduct new education, training and research programs, and improve existing ones; (5) create a national seismic network; and (6) create a monument from a collapsed historical bridge.

NOTE: This report is available in Spanish.
NOTA: Este informe está disponible en español.
PROLOGUE

In this excellent report the authors summarize the behavior of most types of buildings and infrastructure which were subjected to the effects and damage of the February 27, 2010 Chilean earthquake and tsunami.

The General Engineering Observations are very appropriate and I agree with the assertion that, from the human loss point of view, the Chilean public built infrastructure as well as the private provided the people with a level of protection without equal worldwide. Chapters 3 and 4, Detailed Engineering Observations and Emergency Building Inspection and Emergency Response, respectively, give a clear idea of the occurring damage, of the losses that this damage produced, and that there exist problems in the safety evaluation of the damaged buildings. The losses occurring due to a seismic event should be evaluated, adding, amongst other parameters, the civic and social outcomes of the earthquake effects, which are not considered in this report. For example, the press has published that civic turmoil occurred in certain areas. Consequently, the civic preparation, as well as the technical preparation covered in this report, should be an integral part of the emergency response.

Based on their observations and experience, the authors estimate that the losses could be 60 billion dollars, which is double of press reports. I think that, according to the damage presented in Chapter 4 and in other published reports, the losses can reach and even exceed said amount when adding direct and indirect damages. This is a significant figure, close to 71% of the budget that the Chilean Government considered for 2010.

The authors offered 24 recommendations on 6 different topics directed at the nation of Chile in general. These are very good recommendations that, for the most part, will require studies and/or research, which would benefit enormously from the collaboration with foreign scientists and professionals. My experience in this type of collaboration was highly positive and fruitful in the case of the 1985 Mexican Earthquake, where bi-national groups were integrated, collaborating in a large amount of studies. This collaboration was of mutual benefit and learning, achieving significant knowledge advances in the areas of earthquake engineering and seismology, which derived in specific and practical recommendations for codes and procedures. Special attention must be directed to the recommendations addressed to protect what is already built (especially low-cost housing), to reduce the loss of life, and to establish a chain of responsibility that is transparent in the engineering, construction and inspection of buildings and infrastructure.

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THE MAGNITUDE 8.8 OFFSHORE MAULE REGION, CHILE
EARTHQUAKE OF FEBRUARY 27, 2010
PRELIMINARY SUMMARY OF DAMAGE
AND ENGINEERING RECOMMENDATIONS

1. BACKGROUND AND SUMMARY OF THE INVESTIGATION

A magnitude (M_w) 8.8 earthquake occurred in Chile at 3:34 am on February 27, 2010. The epicenter was roughly midway between Talca and Concepción, offshore on the well-known Chilean Subduction Zone Fault. In addition, a multitude of strong aftershocks continued to occur for several weeks along different sections of the fault, some with magnitudes over 6; the strongest so far is M_w=7.1. The earthquake affected a large area of Chile, from Santiago and coastal Valparaíso/Viña del Mar in the North, to well south of Concepción. The affected region includes Chile’s three largest metropolitan areas. The strong ground shaking, which lasted well over 60 seconds and as much as 120 seconds, affected this area from the coast, which is closest to the faulting, to much of the interior of Chile towards the East. Some of the most serious earthquake damage was to cities in the interior, such as Talca. A major tsunami, immediately after the earthquake, caused extensive damage along much of Chile’s most populated coast, from Coronel (near Concepción) in the South to Iloca (northwest of Talca) in the North.

The authors of this report were all in California, USA, when the earthquake occurred. We formed an engineering team to investigate the effects of the earthquake and to observe important new lessons. We arrived in Santiago shortly after the Santiago International Airport opened, five days after the earthquake. We spent about 9 days investigating damage. One of the team members, Dr. Francisco Medina, remained in Chile for another 11 days and continued the investigation. We received the support of engineers and academicians from several Chilean universities, structural and earthquake engineers from Chile, and members of other engineering investigating teams from throughout the world. We received invaluable assistance and access to numerous facilities and buildings throughout the stricken area from other professional Chileans, Chilean government employees, and other technical and non-technical contacts.

We concentrated our research on the following areas (see Figure 1):

1. Santiago and its general Metropolitan Area.
2. Valparaíso and particularly Viña del Mar.
3. Talca and its surrounding area.
5. Talcahuano and its surrounding area, including the coastal region around Talcahuano and Coronel.
6. Constitución, its surrounding area, and the coast to the north up to Valparaíso (by air).

We traveled by car to all of the areas listed in 1 to 5 above. We observed and investigated the effects of the earthquake along and around the Pan American Highway in Central Chile (Santiago to Chillán), the highway from Chillán to Concepción, and the highway from Santiago to Valparaíso, covering an approximate total of 1,000 km. Along the way, we investigated damage to many smaller towns, such as Santa Cruz and San Javier. We observed
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Figure 1. Map of the affected region of Chile, showing the location of the epicenter, generalized shaking intensities (colored dashed lines), our approximate main land route (solid black line), our approximate route by air (dotted line), and the more important regions that we investigated (triangles). Base map: United Nations Office for the Coordination of Humanitarian Affairs (<www.reliefweb.int>)
much of Chile’s food processing industry, wine industry, and other industries located in the vicinity of the Pan American Highway. We investigated briefly some of the heavy industry around Concepción and Talcahuano. We surveyed by air the tsunami damage North of Constitución and its effect on the ground in Constitución and Talcahuano. We were also able to study the effects of the earthquake on several multinational corporations with operations in Chile. We also observed the damage and the effects caused by the earthquake to: (1) architectural features, mechanical equipment, electrical equipment, and all other building features; (2) production and processing equipment in industrial buildings; (3) storage tanks and silos; (4) buildings, roads and bridges, and other structures (in particular, damage due to ground failures); (5) business interruptions caused by damage and other effects of the earthquake; and (6) emergency response in some of the damaged areas.

2. GENERAL ENGINEERING OBSERVATIONS

From an engineering perspective, the Chile earthquake of February 27, 2010 is the most important earthquake in modern history. Because of its size (magnitude \( M_w = 8.8 \)), it is one of the largest earthquakes recorded by modern instruments. The only earthquakes of similar scale have been Valdivia (Chile) in 1960, Alaska (USA) in 1964, and Sumatra and the Indian Ocean in 2004. However, unlike the other three mega-earthquakes of the last 50 years, this one struck a modern country and densely populated metropolitan areas with state-of-the-art engineering, and building practices and codes. It affected a government and a populace that is used to major natural disasters, especially earthquakes, and is relatively well prepared to respond to these challenges. This is clearly evident in the performance of the most modern buildings in Chile – most structures performed well and life losses and injuries were caused primarily by the collapse of older, outdated buildings and by the tsunami. However, as it will be discussed herein, with a minimum investment this performance can be improved and the losses can be eliminated or mitigated. In addition to affecting tens of thousands of older structures, the earthquake affected many structures designed to the latest earthquake engineering codes and engineered and constructed with some of the most advanced engineering principles. These include modern high-rises, industrial buildings, and infrastructure.

The official final death toll (due to the earthquake and its large tsunami) published (May 15, 2010) by the Ministry of the Interior is 521 plus 56 missing, from an affected population of about 12.4 million. This toll is in itself a testament to relatively successful infrastructure engineering and construction practices. Numerous and much smaller recent earthquakes throughout the world have caused many more deaths and, proportionally, much more destruction. Aside from the tsunami-devastated areas along the coast, Chile was devoid of the scale of destruction caused by the major 21st century earthquakes, such as the earthquakes in Afghanistan, China, Haiti, India, Indonesia, Iran, Italy and Pakistan.

In general, the Chile earthquake (1) presents numerous lessons of successful earthquake engineering, and (2) points out numerous areas that require improvement. The earthquake demonstrated for the first time that the buildings designed to modern earthquake engineering standards can withstand a mega-earthquake with minor damage. It also showed that the building codes and the building design practices in Chile and throughout the world must be updated to implement the engineering lessons derived from the damage observed in this earthquake and the tsunami that followed. The worst performing buildings and infrastructure
were the older structures, built before the 1950s. The earthquake shows that older structures in earthquake areas need to be strengthened or replaced to reduce the risk of damage to acceptable levels. This is a major challenge for low-income older housing and small businesses housed in old structures; these are the buildings that suffered most of the serious damage and collapses in Chile, as it has happened in all recent earthquakes throughout the world. The earthquake extensively damaged the interior architectural features and the mechanical and electrical systems of new commercial and other buildings, including hospitals and other critical structures. The Chilean Building (NCh433) and Industrial (NCh2369) Codes include provisions for anchorage design of secondary structures and non-structural elements, but their design, verification and implementation does not fall within the scope of responsibility of the structural engineer; thus, these provisions are largely ignored. These provisions (1) appear to be inadequate, or (2) do not have explicit prescriptions for the protection of these features for the size of earthquakes occurring in Chile. The general architectural and engineering practices in the country seem to forget that these features can substantially increase the overall amount of damage and cause extensive business interruptions, which can exceed the cost of direct damage. This is what happened in this earthquake in some new hospitals, new commercial and residential buildings, government buildings, and industry facilities.

The earthquake points out that Chile needs to upgrade its emergency response to large natural disasters –particularly earthquakes and tsunami. In this area, Chile can learn from the experience and practices of other countries, particularly California and Japan. Chile needs to develop a standardized emergency system for the rapid evaluation of building damage and rating of buildings following a destructive earthquake. More than ten days after the earthquake, many of the affected buildings had not been evaluated by qualified structural engineers. Some severely damaged buildings were being used while they could easily collapse in a strong aftershock. In addition, many people were afraid to return and re-occupy buildings, including high-rise apartment and office buildings that had no significant structural damage and were as safe as before the earthquake.

This earthquake presents us with numerous opportunities for analyzing the damage and the lack of damage in order to advance the state-of-the-art of earthquake engineering, the earthquake risk reduction practice, the risk management practice, and the upgrade of the building codes. Many of these are briefly discussed below.

3. DETAILED ENGINEERING OBSERVATIONS

3.1. Effects of the Earthquake Duration on Building Performance

The strong motion of this earthquake lasted roughly up to 120 seconds. The most damaging part of the motion was about 60 seconds. Other recent destructive earthquakes, including Kobe (Japan) in 1995, Northridge (Los Angeles, California) in 1994, and L’Aquila (Italy) in 2007, had strong ground motion of less than 20 seconds. All of these earthquakes had magnitudes less than 7. Thus, the structures in the strongly affected areas of Chile were subjected to ground shaking that lasted roughly 3 to 6 times longer than the more typical earthquakes that happen more frequently around the world. The amount of structural damage expected in an earthquake is proportional to the duration of the earthquake, as well as the amplitude of the ground acceleration: these relationships are not linear. A longer duration of shaking causes the damage to increase. This relationship is difficult to quantify, partially
because we have so few records of long duration earthquakes such as this one. In this earthquake, much of the damage is due to this effect. In other words, buildings had more time to fall apart as the shaking continued. Because of this difference in duration, it is difficult to compare the performance of structures and all other engineering systems to their counterparts in smaller earthquakes throughout the world. There is not enough prior experience with such large earthquakes. This is one of the reasons why the Chile earthquake of 2010 is so important to engineering, construction, and emergency response.

Building codes throughout the world are based on smaller earthquakes, such as those previously listed; in this respect, Chile is different. The 1960 Chile (Valdivia) earthquake had a magnitude of 9.5, caused extensive damage throughout Chile, and led to important improvements in engineering and construction practices throughout the country. Based on our observations and experience, Chile is the only country in the world that has developed engineering and construction practices suitable for the mega-earthquakes to which the country is exposed. Chilean buildings with many redundant shear walls typically perform much better than buildings in other countries. Other countries, such as the USA (with the exception of the Pacific Northwest and Alaska), are primarily concerned with smaller earthquakes (by Chilean standards) with magnitudes up to just above 8 and durations of around 40 seconds of strong motion.

3.2. Effects of Soil Conditions on Building Performance

The ground conditions below the foundations of buildings influence the strength of the earthquake shaking. Softer soils and recent alluvial soils amplify the ground motion; for example, those soils found below much of Concepción and Viña del Mar. Structures founded directly on rock or hard soil typically perform better. This is evident throughout the affected regions of Chile; buildings of all types were damaged more when sited in areas with soft soils. For example, much of Santiago is sited on very stiff gravelly soils; the damage in these areas was much lighter than in areas with softer soils, such as the new development Ciudad Empresarial, just North of Santiago. In Concepción –a city with much more variable and generally softer soil conditions than Central Santiago– much of the most severe damage was concentrated in areas that also experienced ground settlement and ground failure.

As we traveled along the affected areas of Chile, it was obvious that areas of intense damage, such as the Talca region, alternated with immediately adjacent regions that had practically no damage. Another remarkable marker of the intensity of shaking was the performance of freeway overpasses along the Pan American Highway and elsewhere. These structures are relatively simple and generally similar to each other with relatively minor design differences. In some areas, the overpasses were heavily damaged, and in adjacent areas there was little to no damage.

Our conclusion is that engineering studies of the correlation between structural damage and ground conditions under the damaged structures are necessary for the most important metropolitan areas of Chile. Such studies are needed in order to develop microzation maps of these areas that would in turn be used in the design of new buildings under the requirements of revised and updated building codes and municipal zoning maps. Currently, the codes prescribe different levels of seismic design forces for broad classifications of soil types; there is no requirement for a careful investigation of the actual site conditions.
3.3. Ground Motion Records

Numerous strong motion acceleration records of the earthquake ground motion were recorded throughout the affected area. Some of these records have been published; most are not yet available. These records show, in engineering terms, the exact nature of the earthquake at the location where they are recorded, including the duration of the strong motion. When properly treated, the records define the spectra of motions generated by the earthquake.

The records from the Chile earthquake that have been published to date are some of the longest duration and strongest earthquake ground motions ever recorded. Ground accelerations above 0.50g (50% of gravity) and long durations were recorded in Maipú, just west of Santiago, where overall it is expected that the ground motions had been weaker than in the areas closer to the epicenter. The preliminary indications of these data are that the ground motions exceed in amplitude some of the requirements and specifications in the current Chilean building code by a factor of two to four. This is particularly apparent in the ground motion affecting taller, more flexible buildings.

We heard from academic sources that many of the strong motion records that have been recorded throughout the affected area are not in the public domain. The owners of these data (dam and power plant operators, and others) are reluctant to release some of these records. We acknowledge that vital information is being withheld and cannot be used for purposes of research and development for the public good. The ground motions from this earthquake will probably become the definitive ground motion data for large earthquakes throughout the world. Effectively, these records are the only records that exist to date for very large to mega earthquakes. Previously, the strongest and longest records are from earthquakes such as the Magnitude 7.8 1985 Chile earthquake, and similarly sized earthquakes in California, Mexico and Japan. It is our expectation that the study of these ground motions will lead to major changes in the understanding of large earthquakes and developments in the requirements of the building codes in Chile and the rest of the world.

Unlike other countries, Chile does not have a publicly financed program for the installation, operation, and maintenance of a strong-motion network of earthquake recording instruments (sensors) that substantially cover Chile, including its most populated areas. It seems that public policy decisions have not included seismic risk management as an important endeavor to fund.

3.4. Low-Rise Buildings

Most of the direct building damage throughout the affected areas of Chile was to low-rise buildings, as these are the most common structures in the affected area. Most of the collapsed and partially collapsed buildings were also low-rise and old. Low-rise buildings here are defined as those 4 stories or lower. Damage was basically proportional to the age of the buildings and the requirements of the building codes (if any) at the time of construction.

Old and Non-Engineered Buildings. The most obvious and widespread damage was to old buildings, many of which were not designed to any building code (Figures 2 to 4). We include some newer, non-engineered buildings within this type of structure. In Talca and Concepción, for example, most of the totally or partially collapsed buildings were of two types: un-reinforced masonry (with or without some concrete frames or other components) and adobe construction (Figure 5), including those with timber confinement/reinforcing (“quincha”). These two types of buildings are well known not to be earthquake resistant and
are the types of buildings that cause the most casualties throughout the world. We did not observe any new buildings of this type in the major cities, suggesting that such buildings have not been constructed there for a long time. These are also the types of buildings that have collapsed en masse in past earthquakes in Chile and, thus, many of them had already been removed from the inventory of old and dangerous buildings. The current Chilean code does not mention or explicitly prohibit the construction of these buildings. The code should include criteria for the seismic rehabilitation of such structures. We note here that adobe construction is strongly opposed by most, if not all, practicing earthquake engineers in Chile. However, strengthening of this type of building should be pursued in the case of historical and/or cultural heritage buildings. This is common practice in other countries.

Figure 2. Damage to commercial and residential un-reinforced masonry buildings in Concepción.

Figure 3. Damage to the recently renovated and partially strengthened historic market building in Talca.

Figure 4. A typical street scene (left) and an aerial view (right) of damage on commercial buildings in Talca.
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Figure 5. Damage to a historic adobe church building (left) and a brand new un-reinforced adobe art crafts sale and exposition complex in the vicinity of Santa Cruz (right).

We also observed and studied the poor performance of new buildings of this type in rural areas of Chile (Figure 5, right). This suggests that this type of construction, which should be strongly restricted in earthquake areas, is still practiced in some parts of Chile. Most notably, we learned that the Chilean Council for National Monuments is opposed to any reinforcing of old buildings considered cultural heritage to avoid changing their architectural and structural form. The national press reported ‘Christian Matzner, from the Architectural Commission of the National Monuments Council recalls: “Yungay [a neighborhood in Santiago] is dated from the mid 19th Century. These are old buildings that are standing up, and that have resisted not only this earthquake but all of the previous ones. Adobe construction must not be condemned; one-third of the world is built with mud. The important matter is to maintain it and provide good water protection, such that the water does not seep in, because when it does, the adobe shrinks and expands with temperature, then breaks up.” A good example of the correct conservation is the house of Ignacio Domeyko, built in 1848 and one of the oldest in the Yungay neighborhood. “Not a single clay shingle moved, it is in excellent condition,” says Rosario Carvajal, leader of Neighbors for the Defense of Barrio Yungay.’ These statements explicitly defend the adobe buildings of old Santiago. However, had the accelerations in Santiago’s Barrio Yungay been as high as in Talca or Constitución (over 0.40g), the outcome in Barrio Yungay would have been devastatingly similar to that of Talca and Constitución, where most of these buildings collapsed. Therefore, these buildings must be strengthened for earthquake protection. It is, of course, important that strengthening should not change the cultural and historic characteristics of these buildings, harmonizing traditional building types with seismic resistant features.

**Engineered Confined-Masonry Buildings.** This type of building, confined masonry, is a masonry building (typically un-reinforced brick) built with reinforced concrete frames that are poured in-between the bricks, thus providing interlocking (and some continuity) in the structure (Figure 6). The code allows these types of buildings. When properly designed and built, these low-rise structures perform very well. We observed severe damage primarily to poorly designed and constructed buildings of this type. Some of the taller buildings of this type also suffered damage. It would probably be best to limit the height of confined-masonry construction to that of buildings that have performed well in past earthquakes, and particularly in the areas that experienced the strongest shaking in this earthquake.

**Post-1950 Buildings.** Newer buildings with engineered designs generally performed very well in the earthquake, given the great magnitude and long duration of shaking. Accounting for the lessons derived from previous earthquakes, most Chilean buildings are built of
reinforced concrete and contain massive and numerous reinforced concrete shear walls, which stiffen the buildings and, when properly designed and built, make for excellent earthquake-resistant buildings. Chile is the only country in the world that has such massive and strong buildings. The buildings that performed poorly were located on very soft soils that amplified the ground motion, experienced some settlement, and/or allowed the structure to rock. Other newer buildings that performed poorly had bad reinforcing-steel details and, in general, poorly-connected architectural details. Again, these were exceptions, but we often saw otherwise undamaged new structures with spectacular damage caused by fallen parapets or unusually large and flamboyant architectural features. We observed a large variety of modern buildings completely clad in glass panels, many of which were two stories high. Good attachment details typically prevent any damage to such panels; however, many buildings lost much of their façades, indicating that there was inadequate coordination between the developer, the architect, and the engineer. It is obvious that some engineers took great care to properly connect important architectural details on the façades of buildings; others simply did not.

The large failures and collapses of some few modern buildings (built since approximately 1980) were due, fundamentally, to poor engineering design. At least two apartment buildings in Santiago collapsed, or partially collapsed, due to inadequate shear walls at ground level (defining effectively soft-story buildings), coupled with asymmetric architectural configurations (Figures 7 and 8). These failures were in the town of Maipú where the ground motion was stronger than in most of Santiago (preliminary reports show peak accelerations close to or above 0.50g). Older buildings of this type appear to be relatively uncommon, but as of late, to make room for parking on the ground floor, more buildings have been built with softer (more flexible) ground stories. These buildings were not really tested, as the peak accelerations in Central Santiago are reported to have been just over 0.20g, but based on this performance in the areas with strong shaking, they present a significant hazard to the occupants. The severely damaged and collapsed buildings that we examined could easily have been strengthened before the earthquake to prevent said damage. Several brand new reinforced concrete commercial buildings in the Ciudad Empresarial business park (North of Santiago) were damaged (Figure 9). Typically, they were concrete frame buildings with relatively few shear walls and highly asymmetric architectural configurations. Nearby buildings with more shear walls performed well.

In general, buildings built since approximately the early 1950s performed well throughout Chile (especially in the larger cities where they were most prevalent). The modern earthquake
codes of Chile for these types of structures work relatively well and undoubtedly saved many thousands of lives (Figure 10).

Figure 7. A new reinforced concrete apartment building partially collapsed due to the failure of a first soft-story in Maipú, Santiago. Note the large open garage space with few irregularly placed and severely damaged or collapsed short shear walls.

Figure 8. A new collapsed soft-story reinforced concrete apartment building in Maipú, Santiago. Note that the ground floor (garage) collapsed completely.

Figure 9. A severely damaged brand new reinforced concrete commercial building in the Ciudad Empresarial business park (North of Santiago).

Steel-Framed Buildings. We observed numerous low-rise steel-framed buildings. These buildings generally performed very well, with no damage to light damage. We investigated several two- or three-story steel-framed school and hospital buildings (Figure 11). The schools had no damage, and were often located in neighborhoods that had extensive damage and collapses of older buildings. The hospital buildings also performed well. We also observed numerous industrial buildings that had no apparent structural damage; some of these buildings were very large, low-rise structures (Figure 12).
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Figure 10. Two undamaged reinforced concrete apartment buildings located near the two severely damaged buildings in Figures 7 and 8. Both structures have adequate and more symmetrically distributed shear walls on their ground floors, some with T-ends.

Figure 11. Two undamaged light steel-framed school buildings in Concepción (left) and Talca (right). Both structures were located in areas of heavy damage to older buildings.

Figure 12. This two-story steel-framed commercial building (left) in Talca was undamaged and is surrounded on all sides by severely damaged and partially collapsed un-reinforced masonry buildings. The undamaged industrial light steel-framed building (right) is located in Ciudad Empresarial, near severely damaged new reinforced concrete-framed buildings.

Tsunami Effects to Buildings. Most of the tsunami damage was to low-rise buildings, mostly built of un-reinforced masonry and wood. These structures were simply not designed to withstand even a moderate tsunami and suffered extreme damage. Well designed structures throughout Chile have not been designed to resist the impact of a tsunami, although
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some survived without apparent structural damage. That is also true, with minor exceptions, throughout the world.

We observed modern industrial structures that were severely damaged by the tsunami (Figures 13 and 14). They had survived the shaking, but the incoming and outgoing water and water-borne debris caused most, if not all, of the serious damage. We observed large industrial structures and dry docks that had been simply picked up and moved many meters. Many large fishing boats, other commercial vessels, and containers were moved and deposited many hundreds of meters from their original locations.

Figure 13. Tsunami damage to commercial buildings and the fishing industry in Talcahuano. Note that the streets have been partially cleaned up in the two lower photographs.

Figure 14. Tsunami damage to the Navy run ASMAR ship building and maintenance facilities in Talcahuano.

Chile apparently did not have an adequate system in place to announce and maintain a tsunami warning for a great nearby earthquake. There is also no infrastructure in place to prevent widespread tsunami damage. In that respect, Chile is not alone, as most countries have similar, or worse, systems in place. The damage from the tsunami along the Chile
coastline is an important example of what will happen in Chile again, and what will happen elsewhere around the world, if better warning and response systems are not implemented. Worldwide, some coastal areas with high tsunami risk should consider its possible effects if they were to be developed.

Designing functional structures for a large tsunami is not practical. The workable ways of avoiding tsunami damage are: (1) to site the structures on higher ground away from the water and above the expected design tsunami height; (2) to elevate the structures above the expected tsunami height and support them on a massive structure that would allow the tsunami to run through the lower part of the building; or (3) build protective tsunami walls around structures, or entire areas of towns. The first two of these variants are practical, but are not generally practiced. Tsunami walls could protect important facilities that need to be by the shoreline, and in fact are used for nuclear power plants in tsunami-prone coastal areas. Before the magnitude 7.8 Nansei-oki (Hokkaido, Japan) earthquake of 1993, a massive new, 5-meter high wall for tsunami protection surrounded most of the town of Okushiri. The earthquake generated a roughly 10-meter tsunami and generally destroyed the low-lying areas of the small town. It will continue to be difficult to protect structures until we better understand the expected tsunami heights, and the risks they present to said structures in their wake. This is an area that requires much new research and development, and public education on the risk of a tsunami.

The tsunami hit small coastal communities very hard, devastating local industries that provide work for a sizable part of these communities. Constitución is an example of such a community where the window blind industry was severely damaged by the tsunami. This small city will require special reconstruction planning to reduce vulnerabilities in all sectors (housing, health, education, government, etc.).

3.5. Mid-Rise and High-Rise Buildings

Some of the most significant and costly damage in this earthquake was to modern conventional mid- and high-rise buildings (Figures 15 through 23). We observed two major deficiencies in structural and architectural design and construction:

1. Inadequate shear walls, coupled with asymmetric architectural configurations, caused much of the damage. The concrete shear walls typically had inadequate steel reinforcement details (no adequately confined boundary elements). These added to the severe damage in modern buildings.

2. We often found unusual or more flamboyant architectural features and some conventional details for the bracing of façades (and cladding of buildings) inadequately designed for this type of earthquakes. Their failure caused extensive damage and business interruptions, while the structures themselves were undamaged.

**Damage to Shear Wall Buildings.** We investigated the structural damage to most of the high-rise buildings that were severely damaged in Santiago, Viña del Mar and Concepción. Of all of these structures, only one (the Alto Río apartment building in Concepción) collapsed completely (Figures 20 and 21). An office building, Torre O’Higgins (also in Concepción) partially collapsed (Figures 16 and 17). Given the large number of structures subjected to strong shaking due to this earthquake, this performance implies generally good engineering and construction practices.
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Figure 15. Severely damaged and leaning reinforced concrete apartment building in Santiago.

Figure 16. The 6-month old extensively damaged and partially collapsed reinforced concrete Torre O'Higgins office building in Concepción.

Figure 17. Debris on the street in front of the damaged Torre O'Higgins (left) and an adjacent evacuated office building from Ministry of Public Health in the Bio-Bio Region (right).

The City of Concepción appears to have had significantly stronger ground motion than most of Santiago, where most of the larger and taller buildings are located. This is based on our observations of damage only, because we do not yet have ground motion records from
Concepción. In Concepción and neighboring San Pedro de la Paz, in two minutes nine high-rise buildings 11- to 22-stories tall were damaged beyond repair. The observed tall buildings were all reinforced concrete structures with extensive shear walls. These buildings are stiffer and probably much stronger than comparable buildings anywhere else in the world, where buildings are not designed for such large earthquakes or with so much apparent redundancy. We also investigated several new mid-rise reinforced-concrete frame and relatively flexible buildings with shear walls in a new business park development of North Santiago called Ciudad Empresarial. Some of these buildings suffered near total damage to their upper floors’ interior architectural features while suffering no obvious structural damage; some had significant structural damage not observed in closely located older structures. These structures appeared to be closer to frame structures with shear walls than the typical older shear wall structures (with some frame elements). In effect, these newer buildings are significantly softer than the older style shear wall buildings. This appears to be a new development in Chile.

Our investigations of the damage lead to the following preliminary conclusions and recommendations:

1. The failed buildings had relatively more slender (thinner and narrower) and fewer shear walls, as compared to buildings that were not damaged significantly. The code should prescribe minimum shear wall thicknesses with appropriate reinforcing steel detailing for ductility.

2. The failed buildings typically had asymmetric architectural floor plan configurations as well as vertical irregularities (setbacks) which, in a strong earthquake such as this one (particularly in an earthquake of long duration), cause three-dimensional twisting (torsion) of the building. Some of the structures also had effectively soft-story ground configurations (i.e., discontinuous shear walls at the ground level that are replaced with tall, slender columns, while the core of the building is stiffened) that contributed to or caused the severe damage observed. Nearby buildings that were more symmetrical and had no soft-story configurations performed much better. The code needs to address further the issue of the structural design of architecturally complex structures.

3. We observed that the typical severely damaged buildings had inadequate steel reinforcing details for the majority of the failed shear walls. We observed the following: (1) the confinement of reinforcing steel was inadequate in some cases; (2) the reinforcing steel bars used for ties were often too small; (3) the ties were not properly wrapped around the vertical bars (90-degree instead of 135-degree hooks); and (4) boundary steel elements were absent or not properly confined with stirrups. The Chilean reinforced concrete code has been directly taken from ACI-318, with minor adjustments made especially for boundary reinforcing steel elements. This should be reviewed.

4. Some of the new buildings that we investigated in Chile appear to be much more flexible than buildings that were built just a few years ago under the current code. Basically, the new designs are trying to minimize the number of shear walls and replace them with concrete frame elements. After discussions with local architects and engineers, we understand that this development may be the result of market pressures. Developers are free to ask for several structural designs for a given building. Then, they can pick the one design that is cheapest (based on costs such as fewer concrete walls, less reinforcing steel, etc.) and engage the lowest constructed-
cost engineer to design the final building. Presumably the buildings are code compliant, and even peer reviewed, if designed after 2004. This practice, however, appears to be leading to the construction of buildings that can suffer disproportionately more damage than similar buildings built just a few years earlier.

5. The above four conclusions require extensive field evaluation and assessment. Further comprehensive engineering research and development are necessary to establish in detail what went wrong and what needs to be done in analysis, design, and code review to resolve these problems. This is probably the most important research work that needs to be conducted following this earthquake. The results are important for life safety and for their financial implications. Some of that work has already begun at various universities in Chile (based on our discussions with university professors in Chile and in the US). The work has worldwide implications.

Figure 18. A failed reinforced concrete apartment tower in Concepción. Lower photographs show two failed shear walls.
Most of the high-rise buildings that were damaged severely will have to be torn down. Because of the high density of adjacent buildings, the cost of tearing down some of these tall buildings will likely exceed the cost of their original construction. Thus, the long-term financial cost of these state-of-the-art buildings could be well above twice the original cost, not including the environmental cost. That is not something considered by modern building codes or city planners, as exemplified by similar new tall buildings built in high-density areas or next to critical infrastructure. For example, modern codes require that critical
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infrastructure (such as hospitals and schools) be designed for earthquakes to higher standards than other structures. The issue of building tall buildings next to other tall buildings and critical infrastructure that may have to be torn down after an earthquake at a high cost and inconvenience to the public needs to be addressed. Perhaps the codes need to be updated to require higher levels of design for buildings (1) whose failure would impact adjacent structures and/or essential infrastructure, and (2) that house over 200 people at least 12 hours/day, every day.

Figure 22. A severely damaged reinforced concrete apartment tower in Viña del Mar (left) and a detail of damage to one of its shear walls (right).

Figure 23. A partially collapsed reinforced concrete apartment tower in Viña del Mar (left) and a view of the general area along the waterfront (right).

For cities throughout the world, and especially for the new generation of tall reinforced concrete buildings (including speculative residential buildings), the lesson is simple: we need to study this earthquake, update the building codes to reflect the new findings, and concentrate our efforts on tall reinforced concrete buildings. As demonstrated in Chile, the risks appear to be much higher than most owners and their engineers realize.

Damage to Exterior Building Cladding. This earthquake affected a large number of very modern structures. It caused extensive damage to modern glass cladding in all types of structures. Various conventional architectural details for the bracing of façades (and cladding of buildings) are often inadequately designed for earthquakes and in this case caused extensive damage and business interruptions, while the structures themselves were undamaged (Figure 24).
Overall, the performance of modern façades of mid-rise to high-rise buildings in Chile was good. These façades, called curtain walls, consist of panels of glass or other materials. Most observed buildings with a large percentage of glass cladding performed well, with a small loss of panels. In the case of taller buildings, the cladding that failed was due to (1) structural damage, and (2) larger-than-designed-for structural deformations. Given the size and the duration of the earthquake, the overall performance is surprisingly good. Some smaller glass encased buildings performed not as well. We observed numerous new one- and two-story buildings, such as automobile showrooms, that had lost much of their glass cladding. This could usually be attributed to the flexibility of the buildings. They were generally concrete- or steel-framed buildings with minimal, if any, shear walls to stiffen them. Thus, buildings were flexible and experienced larger-than-designed-for deformations the glass panels could not absorb, breaking the glass. The details for the attachment of cladding should be improved, based on the observed performance, or the buildings should be stiffer.

We recommend a detailed study of the performance of modern types of cladding in this earthquake. It is the first earthquake to affect a large number of buildings with a large variety of cladding. The cladding and its replacement after an earthquake is a significant percentage of the cost of a building.

**Damage to Unusual Architectural Exterior Details.** Numerous modern buildings that had no serious structural damage experienced costly and dangerous damage to unusual architectural features in their exterior design (Figures 25 and 26). Damage to architectural features in the building interiors was also observed.

In Talca, for example, two important new public buildings will stay shut down for an extensive period because of damage to (1) exterior architectural features that had no structural function, and (2) interior architectural features and other building contents. These were a
building at the regional public hospital (see Section 3.7.) and the Regional Appellate Court Building (Figure 26). In both cases unusual heavy architectural features (decorative concrete beams) broke off and fell against the façades of the buildings, causing exterior damage.

![Figure 26. A decorative non-structural concrete beam failed at the new Regional Appellate Court Building in Talca, causing extensive façade damage and forcing closure of the building.](image)

The implication of this damage is that both engineers and architects need to be concerned more with unusual and heavier architectural features that serve only decorative purposes and are not part of the earthquake-resistant structural system. Better coordination between the two professions seems necessary. Also, in the case of function-critical public buildings, such as hospitals, such features should perhaps be limited or should be designed to higher standards. The additional cost would be insignificant, compared with the cost derived from the damage caused by their failure.

### 3.6. Interior Architectural and Equipment Damage

Inadequate or non-existent bracing of interior architectural features, mechanical equipment, electrical equipment, and systems (including manufacturing equipment in industrial facilities) caused much of the damage and financial losses in this earthquake. The lack of attention to the bracing of architectural features and equipment, which are easy to protect, contributed substantially to the overall financial loss from the earthquake. Failures due to the lack of or deficient bracing resulted in extensive and unnecessary interior building damage and prolonged business interruptions. It is our conclusion that the cost of this type of damage is comparable to the cost of the building damage, thus almost doubling the overall financial loss from the earthquake. A more detailed study to estimate the overall non-structural damage to commercial buildings and industrial facilities is recommended.

We observed many modern buildings of all sizes throughout the entire affected region that had suffered heavy damage to their interior architectural finishes and equipment (Figures 27 through 30).

The worst and costliest interior damage, typically, was the collapse of suspended ceilings in office buildings, hospitals, and all other types of commercial and industrial buildings. Except in areas such as lobbies, residential buildings do not typically have such ceilings and we did
not observe such damage in these structures. The collapsed ceilings were tiles mounted on rather light assembly-kit type structures that are framed with light-metal framing and suspended with light non-structural wires. As the ceilings collapse, they damage piping, lighting, air ducts, and other equipment also suspended from the slab above; then, they damage equipment and furniture below as the tiles fall and break. We also observed heavier un-braced lights and ducting equipment that fell on their own, further damaging the suspended ceilings. All of these architectural features should be braced to avoid this costly damage that causes extensive losses of function and business interruptions. This type of damage is also life threatening; fortunately, the Chile earthquake happened in the middle of the night when most of the buildings with such features were practically unoccupied. For the last 20 years, the California codes have required the bracing of suspended ceilings and other such architectural features. Ceilings braced to those requirements have performed adequately. Chile should consider adopting similar and probably more stringent requirements.

Figure 27. Several new flexible reinforced concrete office buildings in the Ciudad Empresarial business park north of Santiago experienced minimal structural damage but extensive to near total interior damage.

Members of our investigating team have investigated in the field more than 50 destructive earthquakes throughout the world since 1971. For the first time (in Santiago, Talca, Concepción, and throughout the affected areas), we observed extensive life-threatening damage to interior office partitions, including un-braced suspended ceilings and other equipment above them. In some new office buildings, all of the interior partitions and non-structural walls on the higher floors collapsed. The partitions that collapsed were not anchored adequately, if at all. Nearby partitions that were anchored directly to concrete elements of the structures did not experience comparable damage. The worst damage was in the upper floors of flexible buildings. This is due to the increase of motion with height (for mid- and high-rise buildings) during the earthquake because of amplification as the building
moves. We often observed moderate damage on the ground floor and heavy damage on the top floor of mid-rise buildings. Severe damage in higher-rise buildings was also observed.

Figure 28. This 21-story reinforced concrete apartment building in Talca (left) was structurally undamaged but was unoccupied two weeks after the earthquake because of equipment damage. The unanchored water heaters (right) moved and ruptured connecting piping.

Figure 29. Typical interior damage to a high-rise in Santiago (left) and a low-rise in Talca (right).

Figure 30. Near total interior damage to two structurally undamaged buildings in Concepción. Note the pile of interior debris (left).

We observed damage to all kinds of equipment in all types of structures and industrial facilities. The damage was due to the lack of (in most cases) or inadequate anchorages, and not to any inherent functions of the equipment. These are simple details such as tying down
equipment to the floor and walls so that they cannot fall over or slide and tear out piping, electrical, and other connections. This type of damage causes extensive business interruptions. For this seismic event, three weeks after the earthquake, we observed that most industrial facilities had not restarted full operations and many public and commercial buildings in cities like Concepción were not occupied due to damaged equipment. For example, some hotels had no hot water because their water tanks had collapsed on their legs and severed the water lines. Because of that kind of simple damage, many hotels were closed, and those that were not were charging lower room rates to account for the inconvenience. Strengthening such features before an earthquake is a simple and extremely cost effective form of insurance against business interruption. When life-threatening damage is involved (which is frequently the case in industrial facilities), anchorage and bracing of equipment should be considered in the codes. This is explicitly stated in the Industrial Structures Code (NCh2369).

At the time of preparing this report, four weeks after the earthquake, the overall direct damage cost is estimated (as reported by the media) to be 30 billion US dollars and the indirect damage cost due to lack of production is estimated at 7.6 billion US dollars. In general, these preliminary estimates do not include much of the buildings’ interior damage (which is very significant in this case), business interruptions, and inventory losses in the industries affected. If all these financial losses and other losses (for example, the loss of market share) were included in the estimate, then the total financial losses would roughly double those estimated preliminarily for the direct damage. Thus, our estimated total financial loss would be on the order of 50 to 60 billion US dollars. This is a very rough estimate based on our observations and experience with such estimates in many past earthquakes. As stated earlier, most of these losses can be avoided with relatively simple engineering and good risk management practices.

3.7. Other Structures

**Hospitals.** Hospital performance during the earthquake was directly related to the age of the structures, to the history of seismic strengthening and rehabilitation of the older structures, and to the quality of bracing or anchoring for the interior architectural features and equipment (mechanical, electrical, medical, etc.). We investigated in detail one major hospital, the Talca Regional Hospital (Figures 31 through 34), where we observed the following:

1. One of the new buildings had major exterior damage to heavy concrete decorative architectural elements and its parapets were improperly connected to the structure and collapsed (Figure 31). The hung ceilings collapsed in several areas, damaging building contents and expensive medical equipment. The building will be closed for several months to repair the damage, at a time when it is badly needed in the aftermath of the earthquake (Figure 32).
2. A new steel-framed building had minor structural damage and remained operational.
3. Older buildings suffered extensive damage and will have to be replaced (Figure 34).
4. Bridges (passageways) connecting two buildings were not detailed to account for the differential movements between the two buildings and were damaged (Figure 33)
5. All of the hospital buildings suffered damage due to the collapse of the suspended ceilings, other interior architectural features, and equipment (mechanical, electrical, heating and ventilating, etc.).
6. All of the above damage described above, at the time of our visit, shut down about 70% of the useable surface capacity of the hospital.
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Figure 31. Two new buildings at the Talca Regional Hospital. The steel framed building (left) has minor structural damage. The reinforced concrete structure (right) is shut down due to damage to decorative exterior elements and interior suspended ceiling collapse. Note the leaning forward decorative column and the poorly attached and collapsed parapet (right).

Figure 32. Typical interior damage inside the Talca Regional Hospital. Several buildings at this hospital suffered similar and extensive damage.

Figure 33. Typical exterior architectural damage (left) and non-structural damage to a connecting walkway bridge (right) at Talca Regional Hospital.

If the Talca Regional Hospital is typical of hospital facilities throughout Chile, then the country needs to initiate a major program to strengthen hospitals to earthquake standards, upgraded as recommended in this report. Such programs exist in several other places including Japan, California, and Istanbul (Turkey).

Historic Public Buildings. We reviewed numerous historical buildings, including early colonial buildings and others used as public offices, museums, etc.

We conducted a damage and performance review of the Intendencia Regional del Maule. This historic three-story building, which was not originally designed for the current
earthquake knowledge, was heavily damaged. The building had recently undergone an extensive architectural renovation. The damage consists of cracked and severely damaged unreinforced masonry walls, interior and exterior architectural details and finishes, and extensive structural damage to its load bearing elements (Figure 35). The local government representative who escorted us during the building inspection expressed concern that the local government did not have the funding to strengthen and repair the damaged building and a number of other buildings in a similar situation; in addition, they did not expect significant help from the central government. Whether or not that was the case, numerous buildings and their local government owners face the same situation.

Figure 34. Severe structural damage to older Talca Regional Hospital buildings.

Figure 35. The severely damaged historic Intendencia Regional del Maule in Talca.

3.8. Infrastructure

The earthquake caused widespread damage to public and private infrastructure in the affected area. The damage included structural failures, ground failures that resulted in damage to infrastructure, and equipment and architectural failures that caused infrastructure disruptions. We investigated a large number of infrastructure projects, including the Santiago International Airport, and several damaged and collapsed bridges along the main highway system that was affected. The following are our brief observations on some of the infrastructure that we investigated and/or observed in some detail.

Overall, the engineered infrastructure performed relatively well for an earthquake with a magnitude of 8.8. For example, relatively few highway overpasses (bridges) collapsed and the overall damage did not cause major emergency response problems. Again, the earthquake presents numerous examples of good engineering and numerous examples of what could be
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done better. The one major exception to reasonably good performance of infrastructure was the overall response to the tsunami (see Section 3.4.).

Santiago International Airport. We observed the damage to the main terminal and some of the adjoining and nearby structures. We did not investigate any of the non-building aspects of the airport operations.

The airport main terminal structure is a large three-dimensional tubular braced steel frame. We did not observe any damage but learned from academic sources in Chile that some structural damage occurred to connections at a few locations. The structure of a large portion of the terminal that we investigated performed very well, without any apparent structural damage. However, other non-structural damage closed the terminal for a few weeks, and at the time of writing this report, it remains partially operational. There was extensive damage to heavy suspended ceilings; large portions of the ceilings collapsed and would have injured many people if the terminal had been heavily occupied. The worst damage related to the closure of the terminal was to the pedestrian bridges that connect the terminal building to the adjacent elevated reinforced concrete roadway structure (Figure 36). The latter is built as a separate structure. During the earthquake, the terminal structure and the elevated roadway vibrated independently, causing differential movements between the two structures. Consequently, the bridge supports located over these two structures moved in differential fashion. The bridges were not detailed to accommodate these differential movements and collapsed. The bridges should have had a different earthquake-resistant structural detail, such as sliding joints, to accommodate the differential movements. Thus, a minor structural detail caused an extensive disruption to the operation of the country’s main airport. We recommend that the government of Chile conduct a risk assessment of its main airports (and other important infrastructure) and undertake a long-term risk reduction program to reduce earthquake risks to acceptable levels. The present code does not explicitly mention airports as essential facilities, but it can be interpreted that they are; as such the code prescribes 20% higher seismic design forces, which may be low when compared with other codes.

Santiago Metropolitan Train. The Santiago Metro System consists of tunnels, aerial structures, tracks on grade leveled with the road or sunk with retaining walls on the sides, stations, operation buildings, power substations, and other ancillary buildings. The system suffered no structural damage. Furthermore, equipment and non-structural elements had no damage, and only some minor architectural cladding in some stations became loose and fell. After a standard inspection, the system was up and running normally within 24 hours.

Figure 36. The lightly damaged International Terminal in Santiago (left) and a typical damaged interconnecting bridge (right).
Transportation Infrastructure. The earthquake epicenter was close to the primary transportation network of Chile and its three largest suburban areas: Santiago, Valparaíso/Viña del Mar and Concepción. All of the transportation systems suffered damage and disruptions. However, because of overall good design and construction and of quick recovery and repair efforts, the road network was effectively functional in a few days. We were able to drive along most of the affected area five days after the earthquake, excluding areas along the coast that were inundated by the tsunami. There were frequent detours due to minor and some major damage along the entire length of the four-lane Pan American Highway between Santiago and Chillán.

The primary damage to the highway system was: (1) roadbed and embankment failures, primarily due to ground and fill failure in improperly compacted soils (Figure 37); and (2) the collapse of bridges and viaducts along the main highways where the girders collapsed from their vertical supports (Figures 38 to 40). We also observed failures due to soil liquefaction in and around Concepción. Approximately half of the more severe highway failures and collapses were due to the lateral movement (spreading) of embankment fills. Most of these occurred in areas of very soft soils, such as along river courses or in higher inadequately compacted embankments.

Several bridges collapsed or had serious damage at vertical supports. Most of the collapses were at abutments or in viaduct vertical supports where the girders supporting the roadbed slid and fell off their inadequate seats (Figure 38). We did not notice any severe column failures, except at a few locations where settlement of the column foundation had caused lateral movement. Most collapses we observed occurred at skewed supports. Fortunately, along the viaducts built with independent structures on each direction, only a few bridges...
failed at the same location in both directions simultaneously. Therefore, it was easy to detour traffic in almost all cases. At one viaduct over the Bio-Bío River in Concepción where a segment collapsed, vehicular traffic was restored with a temporary steel truss bridge erected in a few days (Figure 38, right). However, the authorities had to restrict traffic because the non-collapsed part of the viaduct suffered extensive damage to its girders due to vertical pounding, suggesting that the earthquake had a strong vertical component. In and around Concepción we also observed road damage due to soil liquefaction.

![Figure 39. Bridge failure due to column settlement in Concepción (left) and a collapsed old masonry arch bridge along the Pan American Highway (right).](image)

Our California based team noticed immediately that in Chile the typical freeway and road overpasses and their columns and piers looked remarkably like their retrofitted counterparts in California. The California bridges were strengthened following the collapses of bridges, elevated causeways, and viaducts resulting from California’s 1989 Loma Prieta and the 1994 Northridge (Los Angeles) earthquakes. The Chilean bridges are typically robust, with large columns and various details to prevent the slippage of girders from their supports. Most of the bridges were undamaged or had minor damage at their supports. We did not observe any failures of modern columns or piers caused by inadequate structural design.

We investigated two major collapsed bridges. Both of these bridges were scheduled for replacement because they were not properly designed for the earthquakes we now know occur in Chile. One, the long Bio-Bío Bridge (causeway) in Concepción was a concrete frame bridge (Figure 40). The other bridge was an old tall masonry arch bridge located on the Pan American Highway (Figure 39, right).

We recommend a detailed review of the performance of the highway system during this large earthquake coupled with an overall risk assessment to determine what remaining components need improvement. Similar programs have been completed in California and Japan.
The main rail line between Santiago and Concepción is parallel to the Pan American Highway. We observed damage at the abutments of several old steel truss bridges. In at least two cases the foundations of the abutments had settled due to ground failure or inadequate foundation design.

The new railroad control center building in Concepción (belonging to EFE, Empresa de Ferrocarriles del Estado) is located on very soft soil or fill, a few hundred meters from the collapsed Alto Río apartment building. The three-story building had no significant structural damage. It is a reinforced concrete frame building with braced steel frames forming its two staircases. However, due to lack of an adequate earthquake bracing system, it suffered major damage to the contents of its upper two floors: suspended ceilings, architectural finishes, suspended ventilation ducting, lighting equipment, partitions, etc. (Figure 41). Computers and control equipment toppled. The center will be out of operation for several months while the non-structural damage is repaired.

![Figure 41. The train control center in Concepción was structurally undamaged (left). The interior was damaged extensively (right).](image)

**Power Generation, Transmission, and Distribution.** We did not visit any power generating facilities. Instead, we received informal academic reports of damage to such facilities. We observed failures of the transmission and distribution systems due, primarily, to ground failures or the collapse of structures in distribution facilities. We observed some damage to substations, but we did not have the opportunity to conduct any detailed studies. Given the size of the earthquake, we highly recommend a detailed study of the performance of the total system and important individual facilities. We recommend, based on our detailed experience with many other earthquakes and power systems (particularly the 1985 Chile earthquake), that Chile power systems be reviewed and strengthened to acceptable levels, based on risk and cost-benefit analyses.

**Ports.** The team only visited the Port of Talcahuano, which was severely damaged due to the tsunami. The Navy’s autonomous shipbuilding company (ASMAR) facilities were in complete disarray (Figure 14) and the workers were in salvage mode.

**Communications.** During our visit, most of the communication systems were up and running. We made extensive use of land and mobile phones, with sporadic down time, especially after aftershocks. However, it was widely reported that there was a total collapse of the communication system immediately after the earthquake. This is a strategic emergency failure problem that needs to be addressed. An earthquake-resistant emergency communications system should be available at all times, before, during, and after an earthquake.
3.9. Industry

**General Comments on Industry.** We observed the general performance of a large number of industrial facilities, and were able to review several in detail (Figures 42 and 43). In general, much of the industry of Chile in the strongly affected areas of the country was not fully operating three weeks after the earthquake. Most of that can be attributed to damage to equipment and the resulting business interruptions. Structures, particularly older structures, suffered extensive damage. Newer structures throughout the region, especially the ubiquitous light steel-framed industrial structures, appeared to perform reasonably well. Members of our team investigated in detail the performance of 15 facilities of a major, multinational food industry company. Most of the damage to the facilities was to unanchored or inadequately braced equipment and their connections.

![Figure 42. A failed reinforced concrete structure supporting an elevated water distribution tank near Santa Cruz (left) and a collapsed steel water tank at the Santiago International Airport grounds (right).](image1)

![Figure 43. Collapsed water cooling towers shut down operations at a major refinery (left). Structural damage to a steel tower (right, left structure) and other equipment shut down operations at a major steel mill. Both of these plants are near Concepción.](image2)

**Food Industry.** The food processing industry suffered significant damage. A large number of storage, distribution, and packaging plants were observed. Throughout the visited areas, we observed many of the facilities located along the Pan American Highway, where they are adjacent to highway and rail transportation (Figures 44 and 45).

Around half of all silo storage facilities that we observed had one or more collapsed silos. On the order of 20% of all observed silos collapsed (Figure 46). It appeared that only full or partially-full silos collapsed. The damaged and collapsed silos varied from small to very large, from old to new, and from those supported directly on their concrete pads to those on elevated braced steel-frame supports. Collapsed silos included reinforced concrete, corrugated steel, and other type of materials. The poor behavior of silos is probably due to...
inadequate design for the long duration of the earthquake. As many of the collapsed silos were relatively new, the industry should reevaluate its design criteria. Team members observed similar but less frequent collapses due to the 1985 earthquake, which had a much shorter duration.

Figure 44. Severe inventory damage (left) and severe structural damage to buildings caused by the collapse of inventory (right).

Figure 45. The earthquake caused extensive business interruptions to all types of industries, due to structural damage (left) and equipment and inventory damage (right).

Figure 46. Collapsed steel and concrete silos, new and old, throughout the entire affected area.
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The fruit export and packing industry had similar problems, but to a lesser scale.

**Wine Industry.** The earthquake was centered near the heart of the grape growing and wine industry of Chile. This is one of the main agricultural export industries of the country. It was damaged extensively. Damage was primarily to: (1) stainless steel tanks and their interconnected piping and catwalks; (2) tank supports; (3) stacks of barrels not properly fastened; (4) bins and racks full of bottles; and (5) buildings (Figure 47).

![Figure 47. Structural damage to a winery (left) and seemingly minor damage to stainless steel wine storage tanks that many times caused the complete loss of content (right).](image)

Stainless steel tanks (both large and small) and their contents are the most expensive components of wineries. They have suffered disproportionate damage in past earthquakes, particularly in California and Japan. Damage is due primarily to the lack of good earthquake engineering design of the tanks and their supports. In addition, the stainless steel tank walls are very thin and buckle easily. In general, the tanks rupture easily, spilling their expensive content. The performance of tanks in Chile, as in all other earthquakes in wine and sake producing areas (Argentina, California, Italy and Japan) was poor. The industry has a serious problem with the earthquake resistance of its stainless steel tanks. This earthquake, again, presents a good opportunity to study the damage in detail and to determine how to significantly reduce it.

We visited three wineries in the region of Talca and observed many of the hundreds of wineries throughout the affected region. All of the visited wineries suffered serious damage to the stainless steel tanks. Even though in many cases an attempt had been made to design the tank supports for earthquakes (we observed a large variety of details), none of these exhibited good performance. Almost all of the tanks that were full at the time of the earthquake failed and lost their contents. All of the visited wineries were in areas that did not experience particularly strong ground shaking. Some full tanks had failures at the service door, which produced a sudden negative pressure as the liquid flowed out, with the tank’s subsequent inward collapse. We have been informed that approximately 11% of Chile’s yearly wine production (125 million liters) has been lost.

It must be noted that this phenomenon occurred with the dairy industry for the 1960 Valdivia, Chile earthquake, but the lesson was learned and this time it suffered much less damage.

**Fishing Industry.** The artisan fishing industry in the coastal area affected by the tsunami suffered large losses, estimated in press reports at 39 million US dollars, extending to about 27 thousand fishermen and 4,200 fishing ships (Figure 13, lower left).
4. EMERGENCY BUILDING INSPECTION AND EMERGENCY RESPONSE

We observed that the emergency response to evaluate the safety and suitability of buildings after the earthquake was not standardized and largely depended on volunteer engineers and architects not trained for such inspections. The authorities in charge asked several volunteer professionals to execute these evaluations on a particular building, collecting several opinions for the same building, doubling efforts and using scarce resources during an emergency. Different municipalities and other jurisdictional authorities (such as the regional branches of the Ministry of Public Works) had different ways of tagging buildings, but for the most part buildings were classified in three groups: (1) buildings damaged beyond repair, to be evacuated and demolished; (2) buildings damaged to be evacuated, but awaiting an engineer’s report paid for by the owners to justify a possible occupation and to explain the procedure to repair the damage; and (3) buildings with no damage or minor non-structural damage and suitable for occupancy. Chile needs to develop a countrywide safety assessment program that can be activated in future emergencies. This program can be based on systems developed and successfully tested in recent earthquakes in California and Japan.

Several municipalities and Public Works Ministry branches (where respective private and public building plans are deposited) were damaged and could not be used (Figure 48, left). The National Emergency Office, Ministry of Interior (ONEMI) in Concepción was housed in the top floor of an 8-story tower, which was not damaged. However, the earthquake shook the contents of ONEMI to the point of destruction (Figure 48, right). These offices need to be operable after an earthquake, and future placement of such offices must avoid vulnerable locations.

Figure 48. Severe structural damage to a public works building in Talca (left) and extensive interior damage to ONEMI in Concepción (right).

5. CONCLUSIONS

The February 27, 2010 Chile Earthquake affected 82% of the country’s population. The magnitude of the earthquake, $M_w=8.8$, makes it one of the largest earthquakes ever recorded in the world. This earthquake also caused a tsunami that devastated much of the Central Chilean coast. The earthquake and tsunami caused the confirmed deaths of 521 people, with 56 more missing (as of May 15, 2010). A preliminary report published by the press estimates the value of the total infrastructure losses at 30 billion US dollars. Based on our observations and prior experience with numerous past destructive earthquakes, we estimate that said losses
may double once the building contents and commercial and industrial business interruptions are accounted for.

We observed the largest infrastructure damage in roads and railroads, ports and airports, lifelines (water and energy), industry (agriculture, steel, timber, food processing, fruit packing, etc.), commerce and retail, and housing. The largest life losses were caused by the collapse of old buildings and the effects of the tsunami. The largest economic losses were concentrated in the damage to roads, bridges and ports. There was also widespread damage to the building interiors, including damage to office, commercial and industrial buildings’ contents and equipment.

The buildings that experienced damage can be classified as follows: (1) old, non-engineered, mostly residential and commercial buildings, located outside of Santiago; (2) modern, mostly residential and office shear wall buildings, but with a soft (or semi-soft, in the case of slender buildings) first story; and (3) modern, mostly office and commercial buildings with three-dimensional, relatively flexible frames and exhibiting non-structural elements and contents (such as equipment, furniture, etc.) deficiently braced or anchored.

After observing much of the damage and the engineering and social reasons for it, we conclude that, in great measure, Chile’s infrastructure and modern buildings generally protected the population. We also conclude that it is possible to mitigate future life and economic losses through a systematic program of risk reduction and emergency response preparation, addressing earthquakes and tsunami.

6. RECOMMENDATIONS

The main text of this report contains numerous recommendations based on the observed engineering lessons. Our primary recommendations for Chile are:

6.1. National Program for Damage Prevention and Earthquake Risk Reduction

Establish an overall public policy program for earthquake damage prevention and earthquake risk reduction. This program could explicitly contain some of the recommendations listed below.

6.2. Damage Prevention and Earthquake Risk Reduction

1. Conduct a risk assessment of the entire freeway system of Chile to determine remaining vulnerabilities. Follow this assessment with a program to eliminate or mitigate the risk to acceptable levels by strengthening and seismically rehabilitating vulnerable structures.

2. Conduct a risk assessment of the entire power system of Chile to determine remaining vulnerabilities. Follow this assessment with a program to eliminate or mitigate the risk to acceptable levels by strengthening vulnerable components.

3. Conduct similar programs for other governmental and/or essential agencies and infrastructure, such as hospitals, municipalities, police and fire stations, airports, public works regional agencies, and others that must operate before, during and after an earthquake.

4. Conduct engineering studies of the correlation between structural damage and ground conditions under the damaged structures for the major metropolitan areas of Chile.
These studies are needed in order to develop microzonation maps that would in turn be used in the design of new buildings under the requirements of revised and updated building codes (see Section 6.3.). Coordinate these maps with municipal zoning plans.

5. Conduct engineering studies on the overall performance of confined-masonry buildings. Evaluate whether the height of confined-masonry construction should be limited.

6. Conduct a detailed study of the performance of different modern types of cladding for this earthquake.

7. Establish a program to eliminate the vulnerable private infrastructure (for example, adobe and un-reinforced masonry) by mandating their replacement or strengthening with government subsidies in a way that is respectful, humane, and preserves the local cultural heritage.

8. Identify tsunami-prone areas, develop construction codes applicable to these areas, and regulate the vulnerable urban zones in these areas through municipal zoning maps.

9. Conduct a detailed study of the performance of historic buildings and develop strategies for their strengthening.

6.3. Seismic Code

Conduct a review of the Chilean seismic code and improve it based on lessons derived from this earthquake, including, but not limited to:

1. Develop new design spectra to incorporate the spectra obtained for this earthquake and its aftershocks.

2. Develop more detailed specifications for reinforcing steel to improve the integrity and ductility of reinforced concrete structures subjected to seismic loads.

3. Develop more detailed specifications for non-structural elements, such as purely architectonic elements, equipment (mechanical, electrical, and communications), ceilings, etc.

4. Develop microzonation maps for vulnerable metropolitan areas (Viña del Mar, Concepción, and other cities with soft and variable soils) and coordinate with municipal zoning maps.

5. Develop a protocol for structural design, review, inspection and materials verification that explicitly avoids conflicts of interest arising from the marketplace.

6. Develop limitations in the code for allowing simplified analysis for structural design only in certain cases. For example, allow simplified analysis only for regular structures, with limited height, founded on firm soils, and with characteristics similar to those that have already been shown to perform well during this and other strong past earthquakes.

7. Develop procedures and criteria to evaluate and rehabilitate existing seismically deficient structures.

6.4. Education, Training, and Research

1. Improve and augment existing programs to include knowledge and operative training to face earthquakes and tsunami to minimize human and material losses.

2. Finance scientific and applied research to improve Chilean seismology and earthquake engineering knowledge to design measures that eliminate or minimize human, cultural and material losses.
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3. Conduct various detailed post-earthquake studies to collect and analyze important engineering data in order to learn all of the lessons that can be derived from this earthquake.

4. Finance the education and generate work opportunities for scientists and engineers specialized in earthquake engineering and seismology.

6.5. Seismic Network

1. Create an organization and provide the resources to sustain the permanent operation of a seismologic network.

2. Design and implement a seismology network of national reach, including strong-motion sensors, data acquisition systems, and communications systems that allow the continuous monitoring of the country’s seismic activity.

3. Develop a quality seismic data bank that is public and open to the world.

6.6. Monument

Use the remains of the collapsed Río Claro Bridge (Figure 39, right) to design a monument to remind Chileans that they live in a country where earthquakes strike frequently and of the resilience of the country to come back ahead after these catastrophic events.
Photographs from Talca by J.M. Aguiló (this page only).