5.0 SITE EFFECTS AND DAMAGE PATTERNS

Site effects were investigated with respect to the structural damage variability within regions characterized by non-uniform soil conditions and/or subsurface geology. The towns of Santiago, Vina del Mar and Talca observations are summarized below.

5.1 The City of Santiago

The city of Santiago de Chile is located in the so-called Central Depression, a basin surrounded by the Main and Coastal ranges of the Andes (western 70◦ and southern 33◦). This basin spans 80 km long and 30 km wide, and it is mainly elongated in the N-S direction, and is characterized by three main alluvial cones that drain the Andean Cordillera: cones of Colina, Mapocho and Maipo. Due to the geomorphological setting, the basin is filled with alluvial sediments (Valenzuela 1978), primarily composed by pebbles, gravels, clays and volcanic ashes (Morales-Jerez, 2002). The pebbles and gravels are mainly located in the eastern and southern part of the basin. Clayey material is mostly present in the north; whereas a transition zone is found in the centre of the valley. In the Pudahuel district, a 40-m-thick layer of ashes (Pudahuel ignimbrite, also known as pumices) is known to seat at the top of the sedimentary column. The stiff pumice probably comes from a major eruption of the Maipo volcano, located at around 120 km to the southeast, at the head of the Maipo valley. According to Bravo (1992) and Gueguen (1994), the mechanical properties of soil deposits in the Santiago basin are listed in Table 5.1.

Figure 5.1. Satellite image and geology map of the Santiago basin

The city was shown to be prone to site effects during the Valparaiso earthquake in 1985 (Monge 1986), when the seismic intensities (MSK) derived from observed damage to one-storey adobe and one storey un-reinforced masonry houses were reported locally much higher (up to IX) than expected (VI) according to regional intensity attenuation relations (Astroza & Monge 1987; Astroza et al. 1993). The highest intensities were concentrated in areas with poor soils conditions, in the fine-grained alluvial deposit and in the ashes deposits (Astroza & Monge 1991). Despite this first-order correlation between soil conditions and damage, however, some parts of the most damaged areas are not built on soft sediments, and some soft sediment areas did not show strong damage during the 1985 earthquake (Fernandez Mariscal 2003); these effects were attributed to the geometry of the basin and the geology of deep sediments.

Table 5.1 Mechanical properties (P- andS-waves velocity, density) at various depths of the three main formations observed in the basin of Santiago (gravels, clays and ashes; after Bravo 1992; Gueguen 1994). Modified from Bonnefy et al (2008)

	Depth [m]	V_s [m/sec]	Density [g/cm^3]
Gravels	0-20	480-720	2-2.3
	200	1300	2.1
Clays	0-20	120-350	1.2-1.8
	50	550	2.1
Ashes	0-20	180-450	1.15-1.7

5.2 Americo Vespucio Norte Ring Road

During the reconnaissance, four bridge sites were inspected along the road Americo Vespucio Norte, the Northern section of Santiago’s ring road. Their locations are depicted in Figure 5.2. The damage intensity was highly variable, with two bridges fully collapsed (DA008a, DA009) and two showing minor structural damage such as shear key cracking (DA008, RL001).

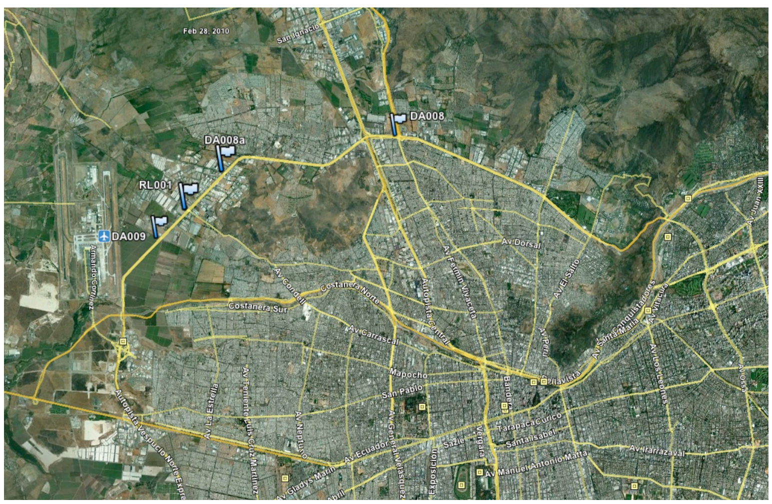

Figure 5.2. Four Americo Vespucio Ring Road bridges visited during the reconnaissance.

Investigating potential correlation between the bridge damage patterns and the underlying soil conditions, the locations of the four inspected bridges are depicted on a geology map of the Santiago Metropolitan Area in Figure 5.3. The soil conditions at the four bridge sites appear to be similar, characterized as Finos del Noroeste which are silts and clays of high plasticity horizontally stratified as thin interchangeable layers. The site conditions at the locations of the four bridge sites are characteristic of Class C/D sites according to the NEHRP soil classification system.

Figure 5.4 depicts the locations of the bridge sites on the geological map by Iriarte-Diaz (2003), along with typical N-S cross section of the valley geology. The depth to bedrock-basement at the bridge sites as approximately interpreted from the cross-section does not show clear correlation with the damage states.

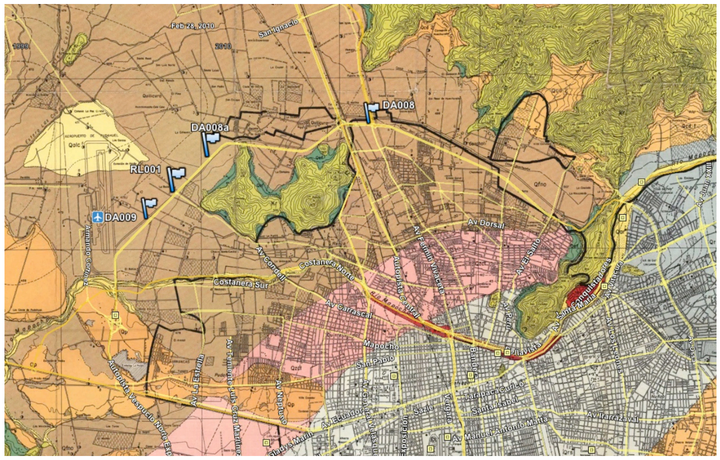

Figure 5.3. Location of the four bridge sites on the geology map of Santiago Metropolitan Area (Dr. Christian Ledezma, personal communication; approximate map overlay on Google Earth)

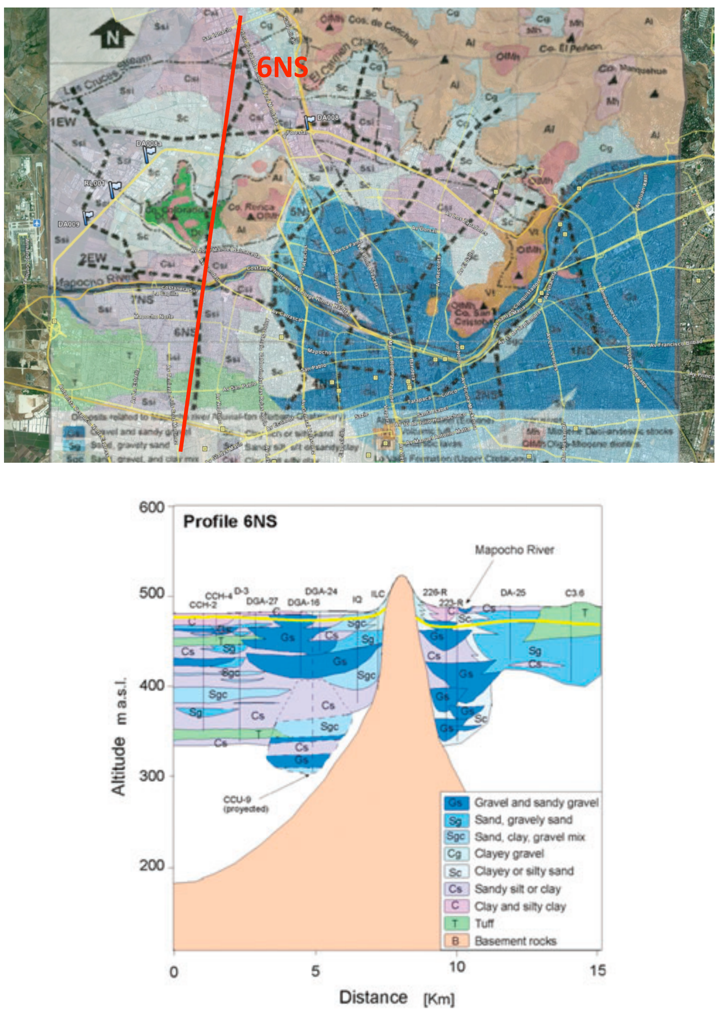

Figure 5.4. Location of the four bridge sites on the map of geological cross-sections in the North-Western part of Santiago de Chile; and Geological cross-section along profile 6NS (Iriarte-Diaz, 2003). Site DA008 (minor damage) is located on clay/silty clay, DA008a (collapsed) on clay/silty sand, and sites RL001 (minor damage) and DA009 (damaged) on sandy silt or silt.

Site DA008 (S33.3660°S W70.6891°) – Paso San Martin

The bridge suffered repairable structural damage, characterized by shear key failure as shown in Figures 5.5a and 5.5b below. Longitudinal and transverse deck movement was also documented, leading to joint damage between the deck segments (Figure 5.5c). The two pile-diameter-deep excavation shown in Figure 5.5d, revealed no foundation failure. According to the local geology map, the soil profile at the site is clay and silty clay.

Figure 5.5. Paso San Martin (S33.3660° W70.6891°, 1122 hrs on 03/14/2010). Shear key failure and longitudinal, transverse deck displacement.

Site DA008a (S33.3759° W70.7476°) – Paso Superior Lo Echevers

The bridge suffered collapse of the east direction deck of the highway (see Figure 5.6). According to the local geology map, the soil profile at the site is clayey/silty sand.

Figure 5.6. Paso Superior Lo Echevers (S33.3759° W70.7476°). Collapse of the eastbound deck of the Americo Vespucio Norte ring road (Source: http://www.flickr.com/photos/consulta_recorridos/).

Site RL001 (S33.3865° W70.7601°) – Paso Lo Boza

The bridge suffered minor damage, primarily shear key failure and subsequent displacement of the deck in the transverse direction (see Figure 5.7). According to the local geology map, the soil profile at the site is sandy silt.

Figure 5.7. Paso Lo Boza (S33.3865° W70.7601°). Minor structural damage of shear keys (Source: Dr. Roberto Leon, personal communication).

Site DA009 (S33.3945° W70.7700°)– Paso Miraflores

The bridge suffered collapse of the east direction deck of the highway (see Figure 5.8). According to the local geology map, the soil profile at the site is sandy silt.

Figure 5.8. Paso Miraflores (S33.3945° W70.7700°). Deck collapse detail (Source: Dr. Roberto Leon, personal communication).

5.3 Ciudad Empresiarial

Ciudad Empresarial is located NE of Santiago downtown. 155 acres were used for the development of a Business Park in a concentric urban layout that hosts multiple corporate headquarters. The soil profile comprises primarily eroded slope material with a shallow water table; the geologic map classification of the site conditions is Finos del Noroeste (Q_{fno}), horizontally stratified thin interchangeable layers of silts and clays of high plasticity. The park comprises highrise buildings that suffered extensive damage during the earthquake. Macroseismic observations at the site were associated with possible site effects. Figure 5.9 shows an aerial view of the business part, Figure 5.10 shows the site conditions prevailing at the site, and Figures 5.11-5.16 depict the sites visited during the reconnaissance.

Figure 5.9. Aerial view of Ciudad Empresiarial, depicting the structures that were inspected during reconnaissance.

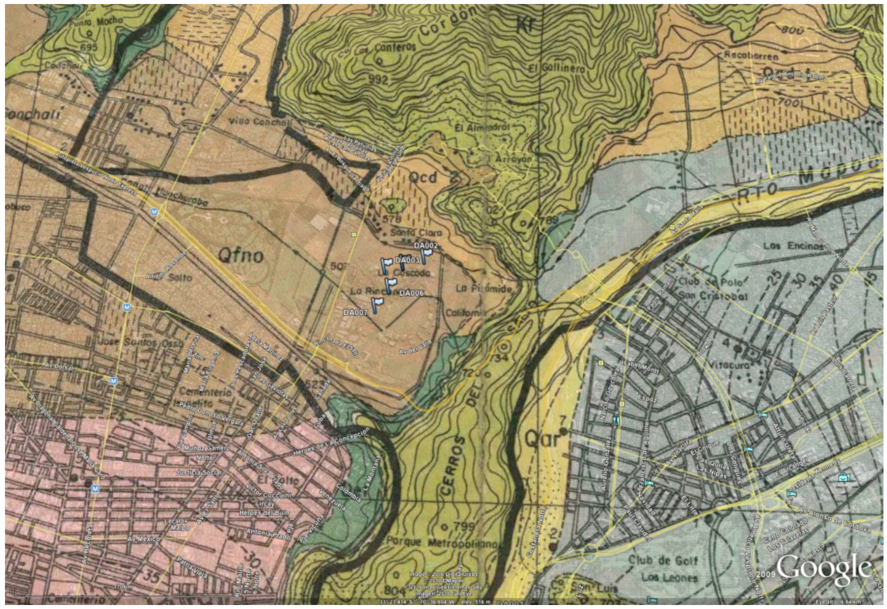

Figure 5.10. Geologic map of Santiago, zoom in Ciudad Empresiarial business park. The geologic material at the site is Finos del Noroeste (Qfno), horizontally stratified thin interchangeable layers of silts and clays of high plasticity.

(a)

(b)

Figure 5.11 (continued)

(c)

(d)

(e)

Figure 5.11. Site DA003 (S33.387985° W70.618815°, 1015 hrs on 03/14/2010) 6-story commercial building. Damage of non-structural elements (glass windows, red brick façade) (Figures 11a,b) and emergency staircase (Figures 11c,d). Evidence of ground deformation (Figure 11e).

Figure 5.12. Site DA004 (S33.387652° W70.617122°, 1047 hrs on 03/14/2010) Identical 7-story buildings connected; damage was observed in only one of the two.

Figure 5.13. Site DA005 (S33.387652° W70.617123°, 1053 hrs on 03/14/2010) Overtopped art.

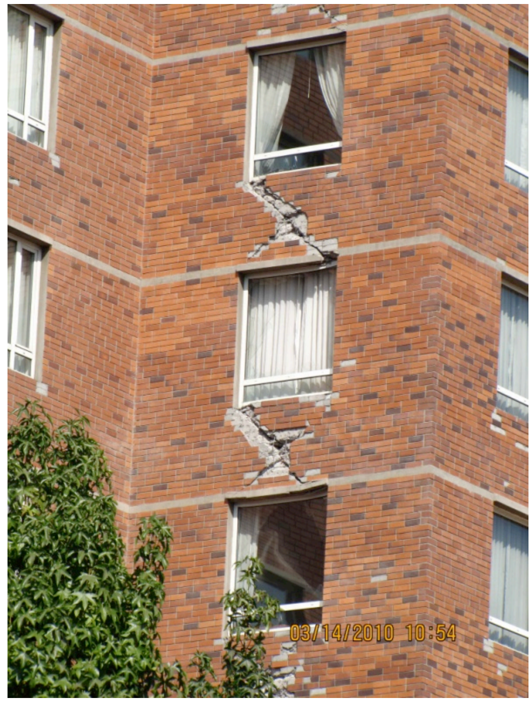

Figure 5.14. Site DA005 (S33.387652° W70.617123°, 1054 hrs on 03/14/2010) 12-story building with severe structural damage.


Figure 5.15. Site DA006 (S33.389586° W70.618349°, 1056 hrs on 03/14/2010) 5-story building, structural damage.

Figure 5.16. Site DA007 (S33.391163° W70.619502°, 1057 hrs on 03/14/2010) Minor external damage – non-structural. Overtopped art.

Overall, the business park was severely damaged, with 7 buildings that failed and were closed to the public. No total collapse was documented and no casualties were reported at the site, while the only evidence of soil deformation is shown in Figure 11e. The damaged structures ranged from a 5- to 12-stories, which to first approximation corresponds to 0.5-1.2 sec resonant periods (0.8-2 Hz).

Bonnefoy et al (2008) conducted extensive ambient vibration measurements in the basin of Santiago de Chile (Chile), evaluating the reliability of the horizontal-to-vertical amplitude spectra ratio method (H/V) as a tool to provide qualitative and quantitative information of site conditions in complex geological media. Results from this study showing the spatial distribution of the H/V peaks according to their frequencies are depicted in Figure 5.17: (red) 0.3–0.5, (blue) 0.51–1.2, (yellow) 1.21–5 and (green) 5.1–10 Hz. Circles display frequencies for clear peaked H/V curves, whereas squares depict frequencies for peaks of low amplitude. The surface geology is shown in background, while the green circle corresponds to the location of Ciudad Empresiarial. As can be readily seen, the resonant frequencies at the site of the business park as identified by means of H/V ratios range from 0.5-5Hz, consistent with the structural resonant periods of the damaged structures. This is an indication that site effects may have contributed to the concentrated structural damage at the site.

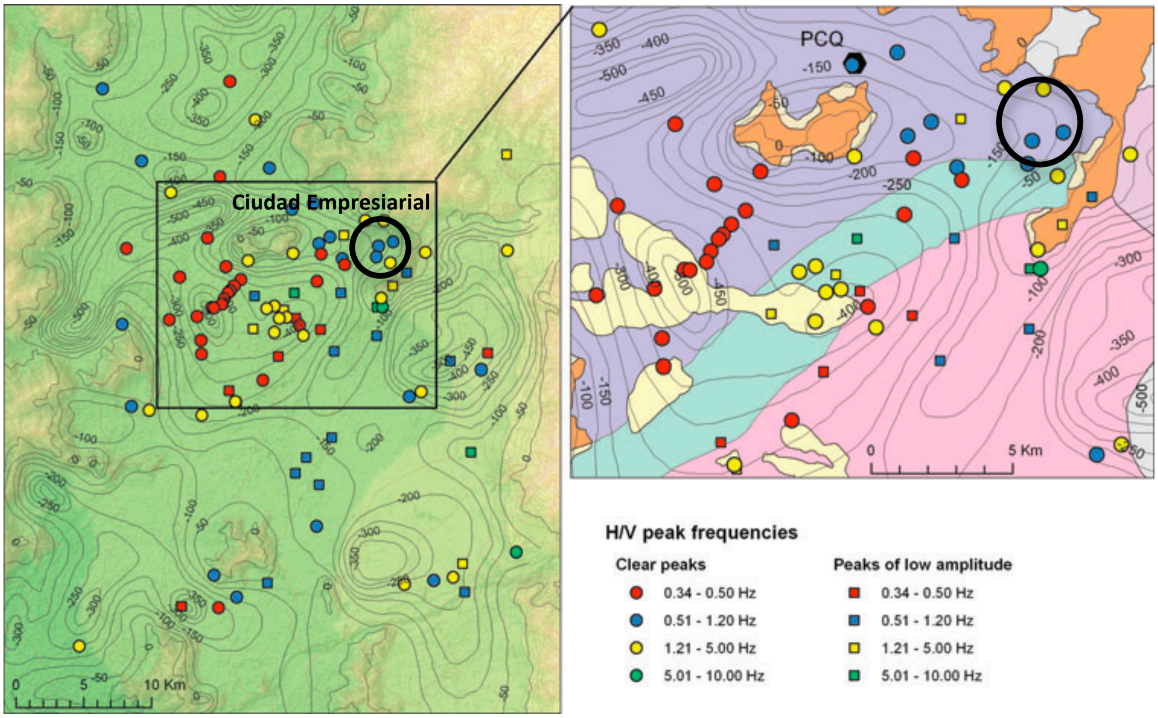

Figure 5.17. Spatial distribution of H/V peaks from ambient noise measurements in NE Santiago, denoted according to their frequencies: (red) 0.3–0.5, (blue) 0.51–1.2, (yellow) 1.21–5 and (green) 5.1–10 Hz (after Bonnefoy et al, 2008). Green circle corresponds to Ciudad Empresiarial.

5.4 Viña del Mar

The municipality of Viña del Mar is located in central Chile (33°02' S, 71°34' W), adjacent to the city of Valparaiso and 120 km (75 mi) northwest of Santiago. The topography of Vina del Mar is typical of a receding coastline whose most notable features are marine terraces and sedimentary deposits (Figure 5.18). Viña del Mar is founded on the marine-alluvial deposits at the mouth of the Marga-Marga River, and the site conditions can be divided into five main categories: (i) rock; (ii) weathered rock; (iii) cemented sand and gravel; (iv) uncemented sand and gravel; and (v) artificial fill. Weathered rock covers approximately 80% of the Vina del Mar region (Moehle et al, 1986), and the water table is located approximately 4m below the ground surface.

Viña del Mar was severely damaged during the 1985 Valparaiso earthquake; extensive study on the structural damage observations can be found in Moehle et al (1986). Strong motion recordings were obtained at the time both in Vina del Mar and the adjacent town of Valparaiso. Celebi (1991) studied the spectral ratios of the recorded motions and showed amplification by as much as a factor of 12 in the North-South direction within the frequency band 0.5-2 Hz (Figure 5.19). This is consistent to a first approximation with the resonant frequencies of 5-20 story structures, typical of the structures in the town of Viña del Mar that were severely damaged.

Immediately following the 1985 Earthquake, a microzonation study was conducted by the municipality of Viña del Mar, leading to the development of maps that identified the location of all existing buildings during the 1985 event, the damage distribution, and the location of demolished structures. Results from this study showed that, if an earthquake causes an intensity I in the surrounding marine terraces, the intensity is likely to be I+1 and I+2 on the slopes leading down to the city and I+3 in the alluvial, fluvial, and colluvial deposits along the Marga-Marga River (Figure 5.20).

Indeed, the same damage pattern was observed during reconnaissance of the 2010 event. Five severely damaged buildings were inspected, all located in the vicinity of the Marga-Marga river mouth and thus founded on soft soil conditions. Note that during the microzonation study following the 1985 Earthquake, the Municipality of Viña del Mar mapped the location of buildings with 5 or more stories (Figure 5.21). The buildings inspected during reconnaissance after the 2010 Earthquake are also shown on this map (also depicted on the aerial view of Google Earth), and are clearly located in the immediate vicinity of the river. Figures 5.22-5.26 depict the structural damage observations of the reconnaissance team.

Figure 5.18. Geology of the Viña del Mar/Valparaiso region. Site conditions are described as weathered rock.

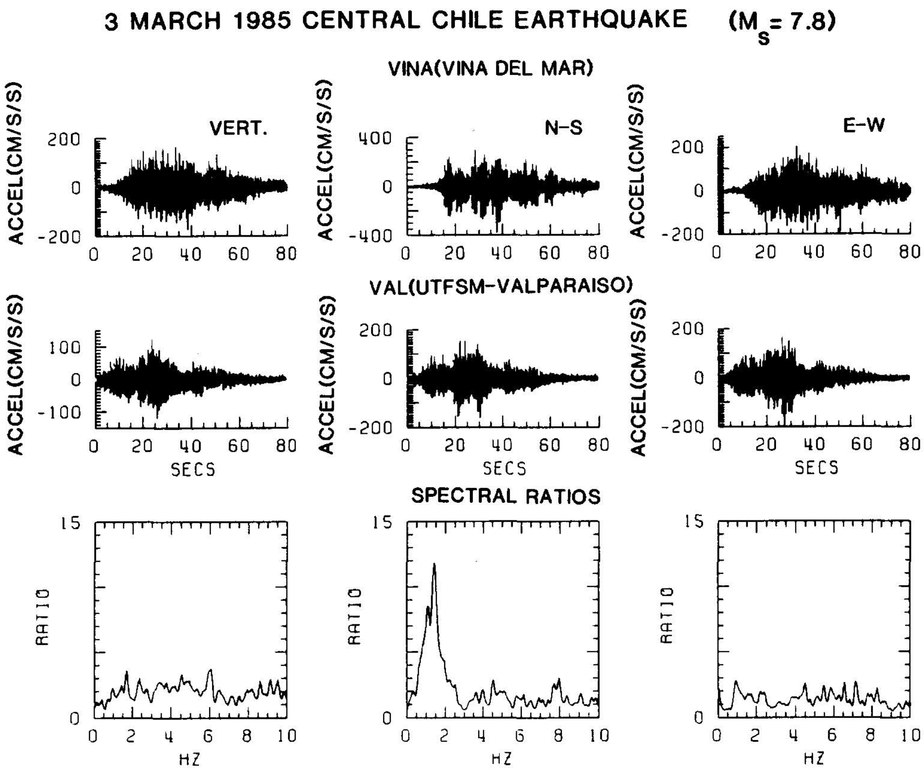

Figure 5.19. Acceleration seismograms of 3 March 1985 Central Chile earthquake (M_S = 7.8) recorded at the strong-motion stations VINA (Viña del Mar) and VAL (UTFSM-Valparaiso) and their corresponding spectral ratios (after Celebi, 2003).

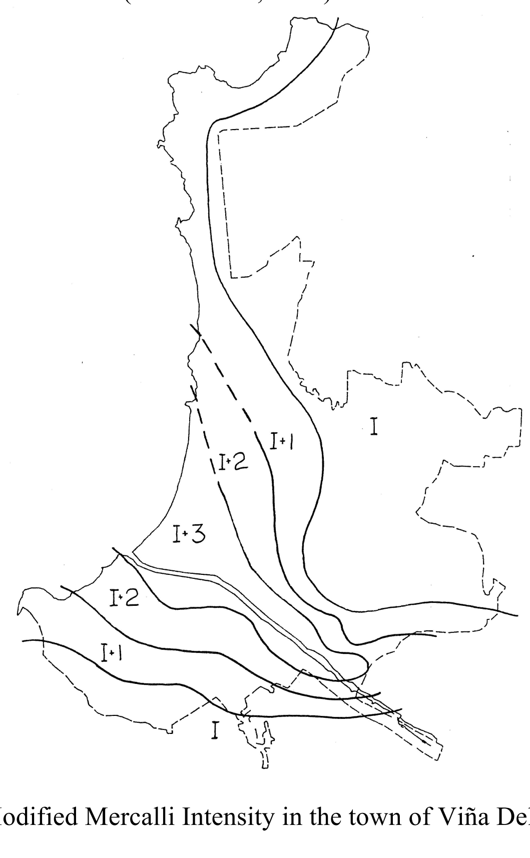

Figure 5.20. Anticipated Modified Mercalli Intensity in the town of Viña Del Mar (Moehle et al, 1986).

Figure 5.21. Buildings inspected during reconnaissance in Viña del Mar. Bottom figure depicts the location of buildings of 5-stories or higher, as mapped during microzonation study that followed the 1985 Valparaiso Earthquake (from Moehle et al, 1986).

Figure 5.22 Site DA017 (S 33.018904° W 71.559206°, 1714 hrs on 03/14/2010) Damaged 9-story building.

Figure 5.23. (continued)

Figure 5.23. Site DA018 (S 33.017386° W 71.557107°, 18:48 hrs on 03/14/2010) Damaged 6-story building. Evidence of ground settlement.

Figure 5.24. (continued)

Figure 5.24. Site DA019 (S33.016045° W 71.551990°, 1916 hrs on 03/14/2010). Damaged 10-story building. Lack of confinement beam-column joints and low quality concrete.

Figure 5.25. Site DA020 (S 33.018678° W 71.556288°, 1953 hrs on 03/14/2010). Diagonal cracks of columns in all the floors of 19-story building.

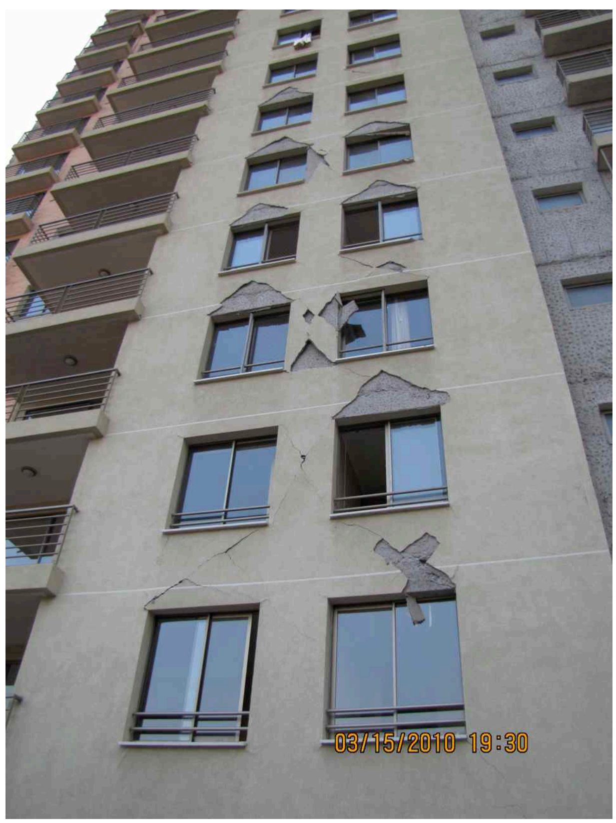

Figure 5.26. (continued)

Figure 5.26. Site DA027 (S 33.020074° W 71.544055°, 1945 hrs on 03/15/2010). Heavily damaged 20-story building, lack of confinement at beam-column joints.

5.5 The city of Talca

The city of Talca, with a population of 200,000 people, is approximately 250 km south of Santiago, 60 km northwest of the epicenter of the 2010 Earthquake. The typical construction type is adobe and unreinforced masonry, which is primarily used for older buildings with 2-4 stories (dating back to before the 1960s-70s). Modern buildings that were designed according to current codes suffered minor, repairable damage, while a large number of adobe and unreinforced masonry constructions suffered significant damage, including disintegration of walls and subsequent collapse.

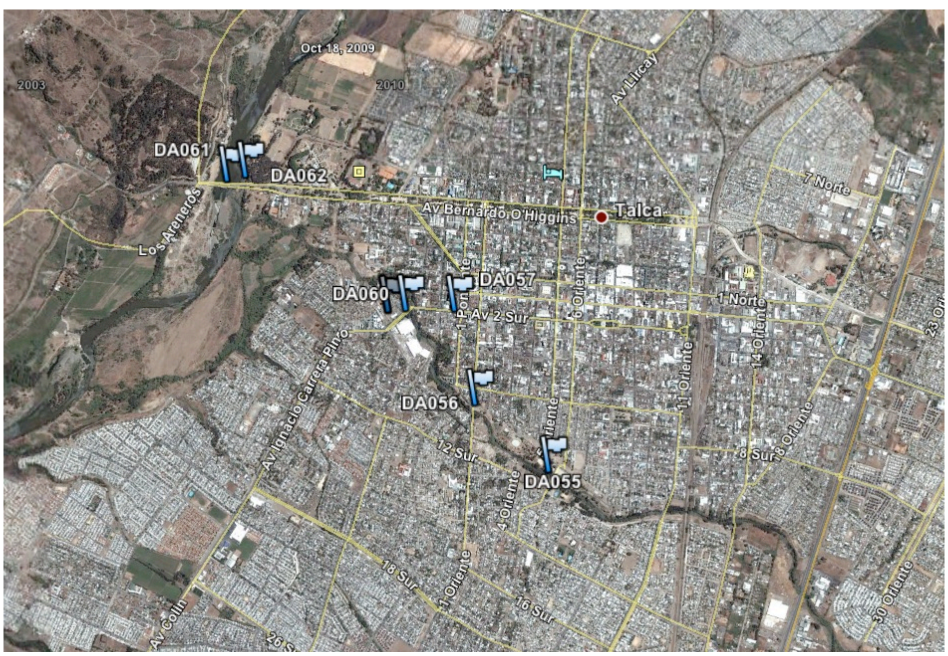

Figure 5.27. (continued)

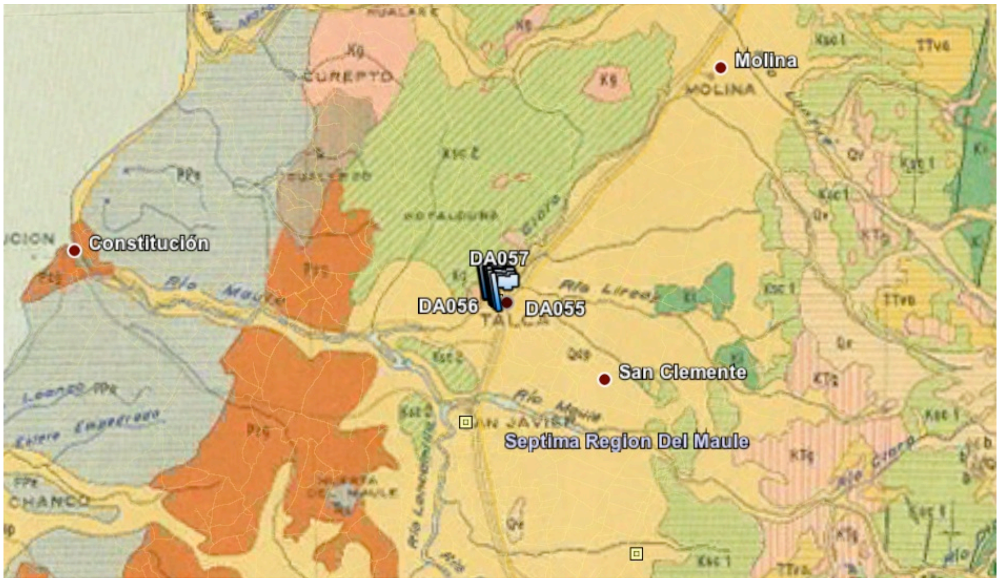

Figure 5.27. Aerial Google earth view and regional geology for the city of Talca.

The aerial view and geology of downtown Talca are shown in Figure 5.27. Alluvial and marine deposits prevail in the region. Structures with major damage or collapsed structures were primarily located near and around the downtown region while the modern (including the tallest, 20-story residential) buildings in the same region suffered minor damage (http://mceer.buffalo.edu/research/Reconnaissance/Chile227-10/City_Talca/default.asp). Four overpasses were inspected along the Maule river with no or minor structural damage. The uneven distribution of damaged adobe structures in the area is potentially indicative of site effects. Figure 5.28 depicts a few pictures from damaged structures located within a few building blocks from the river, and Figure 5.29 depicts modern structures within the same distance from the river with minor damage.

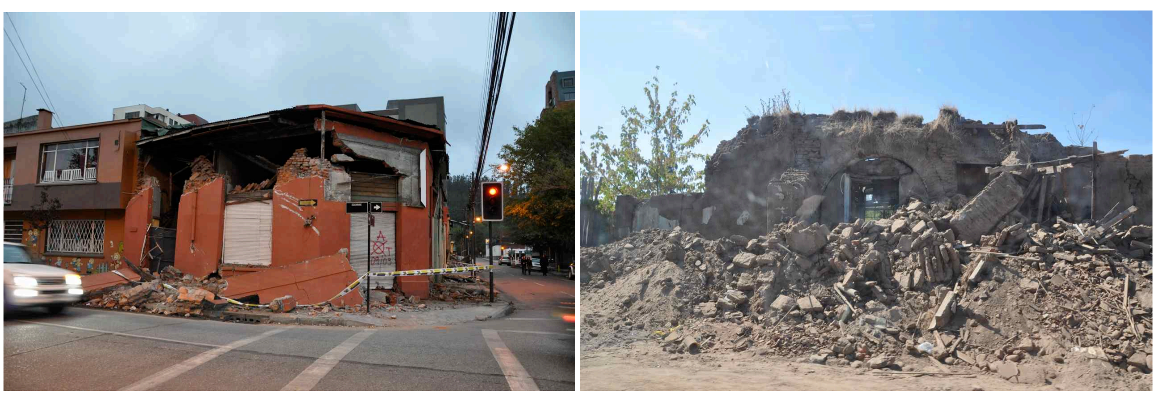

Figure 5.28. Adobe and unreinforced concrete damage concentrated adjacent to the Maule river across Talca (pictures shot from passenger seat while driving).

Figure 5.29. (continued)

Figure 5.29. Modern (engineered) structures adjacent to the river that showed no or minor damage (S 35.437897° W 71.660151°, 1249 hrs on 03/18/2010).

5.6 The City of Concepción

The city of Concepción is built on Tertiary sediments in a valley created by a graben, with metamorphic and granitic formations to the north, east, south, and beneath these Tertiary sediments. A typical geological NW-SE cross section is shown in Figure 5.30, where the sedimentary valley is depicted along with the 3 major faults that run through the area.

Concepción was severely hit by the earthquake of February 27, 2010, and the extensive damage in the downtown area has been associated with site and/or basin effects. In fact, the damage pattern observed during the 2010 event was very similar to the distribution during the 1960 earthquake, for the most part concentrated in the downtown; in both events, the bridges across the Bio-Bio river collapsed. Focusing on the 2010 event, Concepción had seven distinct zones in which buildings and/or bridges collapsed catastrophically. Six of these seven zones are longitudinal in shape and shown in Figure 5.31. The damage is primarily correlated with the location of La Pólvora Fault (see Figure 5.32), which defines the NW edge of the basin; the rest of the damage in Concepción is in the Tertiary sediments between the La Pólvora Fault on the north, the Chacabuco Fault to the south and the Lo Pequén Fault to the east.

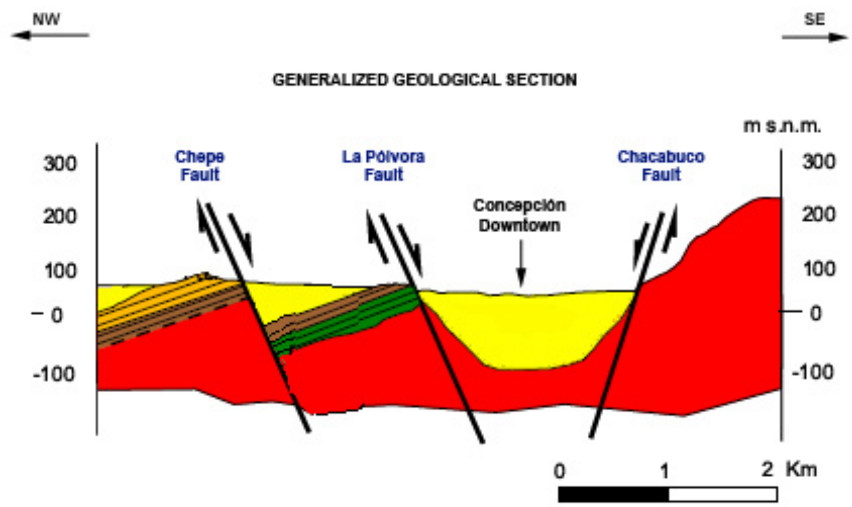

Figure 5.30. Geologic cross-section of Concepción, depicting a sedimentary valley and the major faults running through the region.

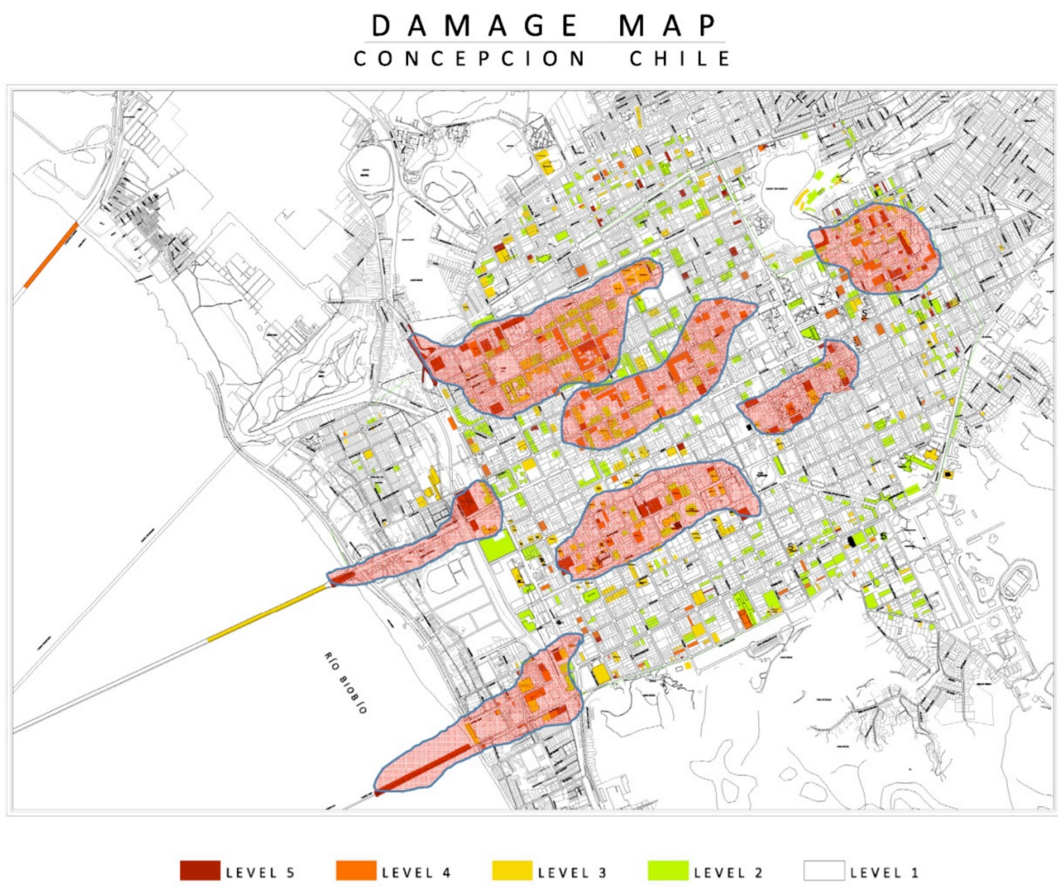

Figure 5.31. Damaged sections in downtown Concepción; 6 out of 7 are parallel to La Polvora fault.

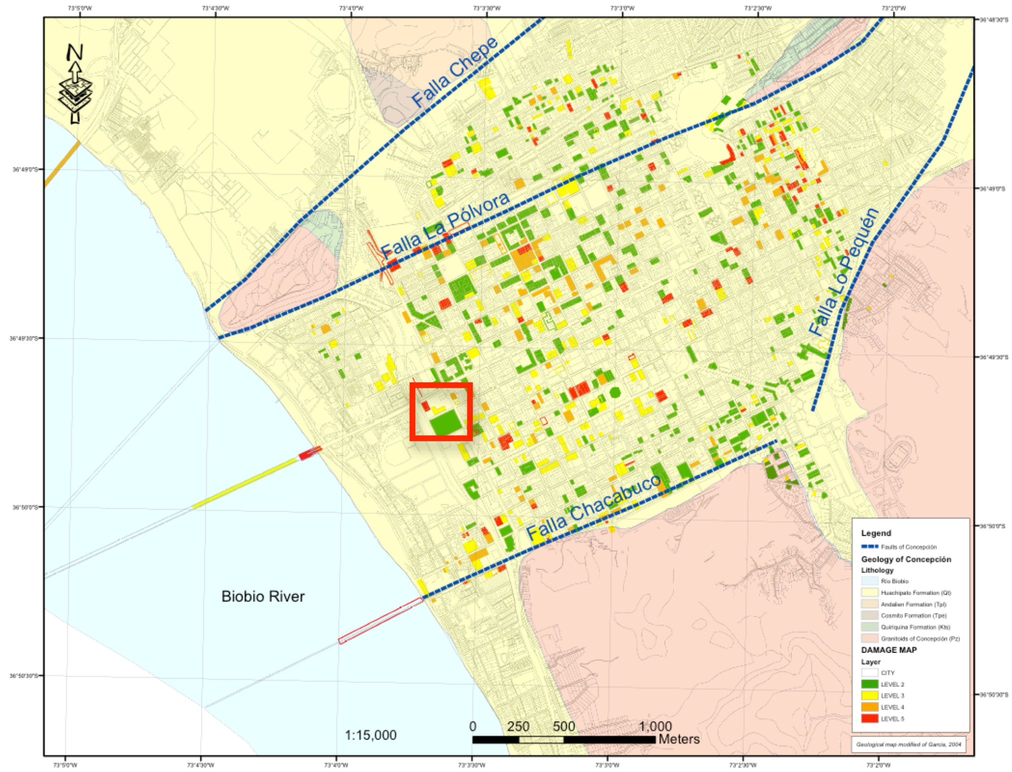

Figure 5.32. Inspected buildings and damage level in downtown Concepción, superimposed on geology map of the region.

Two adjacent 20-story structures were inspected during reconnaissance close to the Llacolen bridge in downtown Concepción (see location in Figure 5.32), one fully collapsed during the 2010 event and the other suffered minor damage and is currently being repaired. The collapsed building was designed using Site Type II (Chilean design code) and the one that did not collapse using Site Type III, which implies different design spectra. While there is no evidence that the soil conditions are indeed different at the locations of the two structures (distance between approximately 20m), the difference in design spectra likely played an important role in the failure of the building. The locations of the two buildings are depicted in Figure 5.33 below.

Figure 5.33. Locations of two adjacent buildings designed with using different site conditions in Conception (map and aerial view).

Figure 5.34. Collapsed structure (S 36.828067° W73.061639°, 1900 hrs on 03/16/2010) designed using Soil Type II conditions.

Figure 5.35. 20-story structure adjacent to collapsed (S 36.828083° W 73.060600°, 1910 hrs on 03/16/2010) designed using Soil Type III conditions, and suffering only minor damage.

5.7 References

Astroza, M. & Monge, J. (1987). Zonificacion sismica de la ciudad de Santiago, in *Proceedings of the XXIV Jornadas Sudamericanas de Ingeneria Estructural,*Vol. 5, Porto Alegre, Brasil, June 29–July 3, pp. 221–235, ANAIS, Porto Alegre, Brasil.

Astroza, M. & Monge, J. (1991). Seismic microzones in the city of Santiago. Relation damage-geological unit, in *Proceedings of the Fourth International Conference on Seismic Zonation,*Vol. 3, Stanford, CA, USA, August 25 –29, pp. 595–601, Earthquake Engineering Research Institute, Stanford, CA, USA.

Astroza, M., Monge, J. & Valera, J. (1993). *Intensidades del sismo del 3 de marzo 1985 en la region Metropolitana y el litoral central. Ingeneria sismica, el caso del sismo del 3 de marzo 1985* (In Spanish), Instituto Ingenieros de Chile, Ediciones Pedagogicas Chilenas S.A., Ediciones Dolmen, pp. 103−117.

Bonnefoy-Claudet S., Stephane Baize, Luis Fabian Bonilla, Catherine Berge-Thierry, Cesar Pasten, Jaime Campos, Philippe Volant and Ramon Verdugo (2008). Site effect evaluation in the basin of Santiago de Chile using ambient noise measurements *Geophys. J. Int.*

Celebi M. (1991). Topographical and geological amplification: Case studies and engineering applications, *Structural Safety,* 10 pp. 199-217

Fernandez Marescal, J.C. (2003). *Respuesta sismica de la Cuenca de Santiago, region metropolitana de Santiago, Escala 1:100000, 1 mapa*. SERNAGEOMIN, carta geologica de Chile, Serie Geologia Ambiental, 1, ISSN:0717–7305.

Iriarte-Diaz, S. (2003). Impact of urban recharge on long-term management of Santiago Norte aquifer, Santiago–Chile, *Master thesis*. Waterloo University, Notario, Canada.

Moehle J., Wood S. and Wight J. (1986). The 1985 Chilean Earthquake: Observations of earthquake-resistant construction in Vina del Mar, Report to the NATIONAL SCIENCE FOUNDATION, Research Grants ECE 86-03789, ECE 86-03604,and ECE 86-06089

Morales-Jerez, F.R. (2002). Definicion de aquiferos en la Cuenca del Rio Maipo (In Spanish), *Master thesis*. University of Chile, Santiago de Chile, Chile.

Valenzuela, G.B. (1978). Suelo de fundacion del gran Santiago (In Spanish with English abstract), *Instituto de Investigaciones Geologicas,* 33, 1–27.