Geotechnical aspects of damages in Concepción, due to the M_w 8.8 Chile earthquake on February 27, 2010

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ABSTRACT
One of the strongest earthquakes ever felt in Chile occurred early in the morning of February 27, 2010. It was the result of a rupture zone, 450 km long just in front of the coastline, from the Arauco peninsula to Valparaiso. The hypocenter was located at the Pacific Ocean in front of a typical town named Cobquecura, about 400 km south of Santiago, and 100 km north of Concepción. This paper delivers some of the observations of a reconnaissance team from the Instituto de Ingeniería, UNAM in the epicentral zone, on the geotechnical aspects related to the observed damages in Concepción, the second largest city in Chile, and its environs. These issues are discussed in this paper, making reference to the effects of the tsunami and other phenomena such as site effects, liquefaction and lateral spreading. Specific cases relating to the behavior of foundations, bridges, silos and embankments, among other structures, are also discussed.

RESUMEN
Uno de los sismos de mayor magnitud que ha sufrido Chile ocurrió la madrugada del 27 de febrero de 2010. Provocó una ruptura de aproximadamente 450 km de extensión, justo frente a la costa de la península de Arauco a Valparaíso. El hipocentro se ubicó frente a una pequeña población típica llamada Cobquecura, muy cercana a la costa, a unos 400 km al sur de Santiago, y a unos 100 km al norte de Concepción. Se exponen en este artículo las observaciones realizadas en esa zona por un grupo de reconocimiento del Instituto de Ingeniería de la UNAM; en este caso, expresamente de los aspectos geotécnicos que pudieron distinguirse dentro de los factores que provocaron la ocurrencia de daños en Concepción, la segunda ciudad más grande de Chile, y sus alrededores. Se exponen aspectos relativos al tsunami y a efectos de sitio y a fenómenos de licuación y desplazamiento lateral; así mismo, se discuten casos específicos del comportamiento de cimentaciones, puentes, silos, terraplenes, y otras estructuras.

1 INTRODUCTION

A moment magnitude M_w=8.8 earthquake, product of subduction of the Nazca plate below the South American plate, occurred at dawn of 27 February 2010, shaking Chile's south-central zone (Barrientos, 2010). As background to this earthquake that affected the zone of Concepción, the earthquakes of Chillán in 1939 and that of Valdivia in 1960, which is the strongest earthquake (M_w=9.5) ever measured in the world, can be mentioned. Co-seismic slip between these plates reached average values of 10 m, with an estimated maximum of 14 m (Barrientos, 2010). It occurred at an approximate depth of 30 km, under the Pacific Ocean bed. It had duration of 90 s and it was associated to a rupture that reached an extension of 450 km, from the Arauco peninsula to Valparaiso, and width of 150 km. Its hypocenter was located in front of the town of Cobquecura, very near the coastline, some 400 km south of Santiago and 100 km north of Concepción. Despite this earthquake's great magnitude, it only resulted in the loss of 580 persons, the disappearance of another 50 and about 800,000 affected persons, a good many attributable to the subsequent tsunami. Economic losses were large, due to considerable destruction of many homes and infrastructure works, with losses amounting to 17% of Chile's gross domestic product.

This article discusses geotechnical aspects that could be distinguished among the factors that determined the occurrence of damage in Concepción, the second largest city in Chile, and its environs. Although the distribution of damaged buildings covered practically the entire city, in accordance with the epicenter's relative nearness, demarcated zones could also be detected which apparently contain less rigid ground in the subsoil, a fact that determined site effects; in those zones there were more marked failures in buildings, bridges, silos, dwellings and other structures, with resulting differential and total settlements, collapses and even complete overturn. This work does not cover Santiago or other cities, where circumscribed zones were also observed with apparent signs of site effects.

On the other hand, it reviews the conditions that determined very extensive phenomena of liquefaction and lateral spreading, as well as the behavior of the foundations for several buildings, discussing the influence of such phenomena, as well as other evident design approach deficiencies.

2 DAMAGE PATTERNS AND SITE EFFECT

The damage observed in Chile was not generalized, and it only became devastating in zones affected by the tsunami. Of course, the largest incidence of damage occurred in the epicentral zone and in the city of Concepción, located some 100 km south from where the rupture began, and where there was considerable amount of damage in tall buildings, bridges, silos, roads, schools, etc.

As has happened frequently in other earthquakes, there were sites in a city with little or no damage, whereas in other areas of the same city most of the buildings were severely damaged or frankly destroyed. A wide range of factors should be considered to try to explain the causes of one and the other behaviors. Assuming the same epicentral distance, explanatory factors to consider are type and quality of construction, and local conditions of subsoil and its topographic environment. Among the more important factors that stand out are resistance and rigidity of geo-materials, depth to basal rock, contrasts in impedance and age of soil deposits. Regarding topographic aspects, the usual amplifications suffered by prominent portions must be distinguished, or the effects of a valley.

Although it is not easy to discern the role of each factor above mentioned, it seems evident that there are local subsoil conditions which a geotechnical exploration must seek to clarify. Structural aspects are not referred to in this article, but it can be affirmed that some of the observed damage is sufficiently generalized so as to think of modifying certain approaches of structural design, such as in reference to concrete walls working under flexo-compression stresses during an earthquake.

The occurrence of site effects is presumed in the cities of Concepción, Santiago and Viña del Mar, derived precisely from local subsoil conditions. Of course, we do not have sufficient information, so we only underline this as a possibility, to be proven. Only in a few cases there were some measurements of subsoil reply to environmental vibration, which are added to the observations on the behavior of structures. These measurements were carried out by personnel of the study group of the Instituto de Ingeniería, UNAM, during the after-earthquake visit.

Land movement at a site due to an earthquake is related mainly to the source of the earthquake, the distance between the source and the place of interest, and the site effect; the latter is the effect that the geological structure of the environment near the place of interest has on the seismic movement observed on the land's surface. Here we describe the basic characteristics of the places where the site effect was very probably predominant in the land's movements; this was done mainly by distinguishing the concentration of damage in relatively small areas.

To support the observations on damage, estimates were made of the predominant frequency of some of the geotechnical structures visited. This, based on field measurements of environmental seismic noise. Due to the available equipment and the limited time of stay at each site, there only are land movement records obtained from natural period sensors, To=1.0 s, in three components, with at least 15 minute duration at each site.

3 DAMAGE ASSOCIATED TO SITE EFFECT

Concepción and its surroundings constitute a thriving conurbation that combines industry and commerce. Port and commercial activities concentrate on the coastal zone, at Talcahuano. Concepción, which is an important industrial center, Chile's second, is located at the mouth of the Bío Bío river; Greater Concepción has about one million inhabitants. It was founded by Pedro de Valdivia in 1550, but was rebuilt in 1754 at its current location, a few kilometers further inland, after it was destroyed by an earthquake in 1751. The University of Chile (Boroschek et al, 2010), through the National Seismologic Service, operates accelerographs at various sites in the country; an accelerograph station in their charge is located at the school of San Pedro in the vicinity of the city of Concepción –refer to the technical report of the National Seismologic Service (2010). The maximum acceleration recorded during the earthquake in reference reached 0.65 g in the north-south component.

Although damage to constructions is appreciated all over the city, a zone stands out where the damage is more accentuated. The zone is a quadrant of no more than one kilometer per side next to the Bío Bío river, at the height of the Llacolén bridge that connects to the commune of San Pedro La Paz; the following collapses occurred there, which are identified in Fig. 6:

- Building 1, totally overturned building with 14 floors, at Calle Padre Hurtado, between Maipú and Av. Los Carrera. This building will deserve particular attention due to its spectacular collapse, Fig. 1.
- Battery of collapsed silos that stored wheat, located at Calle Desiderio Sanhueza and the same Calle Padre Hurtado, some 200 m away from Building 1, Fig. 2.
- Initial panels of the Llacolén bridge (Chile's second longest), which fell to the ground when one of its ends lost support, repeating what occurred during the Valdivia earthquake in 1960, and requiring the construction of a provisional metallic bridge (Fig. 3) to secure passage to San Pedro La Paz after the panels of the "old" bridge (Fig. 4) suffered multiple collapse.
- O'Higgins Tower, whose floors from the tenth upward totally collapsed, Fig. 5. It is one of the tallest buildings in Concepción, with 21 floors.

It seems fit to investigate if that zone of Concepción has particular subsoil conditions that could have defined seismic action of more magnitude on the foundations and structures of the buildings, bridge and silos mentioned. The course and deposit regime of the Bío Bío river, Chile's most plentiful, must have influenced them also.

We found relevant information about the city of Concepción's seismic zoning, but no geotechnical zoning. The city's zoning was prepared recently (Ramírez y Vivallos, 2009), identifying six zones in terms of the dominant periods, detailed gravimetry and surface geology, Fig. 7. The study indicates that the morphology of Concepción is complex because the basin is composed of mountainous chains formed by intrusive and sedimentary rocks, as well as the fluvial sedimentation plain that receives contributions from the Bío Bío and Andalién rivers; these deposits intermingle with colluvial deposits that come from the hill-islands that invade the plain and their rising is associated to covered normal faults in northeastern direction. They observe that the soils were characterized using stratigraphic cuts obtained from 248 soundings that reached an average depth of 12 m; also, the predominant periods were estimated using environmental vibration.

Figure 1. Overturned “Alto Río” building in Concepción.

Figure 2. Silos that failed at center of Concepción.

The dominant periods in the city go from 0.3 to 1.7 seconds and are distributed in such a way that the larger periods correspond precisely to the city’s flat part, and the smaller ones to the transition to the mountainous zone.

As mentioned before, the five sites indicated in Fig. 6 with collapsed structures fall precisely in Zone I of Concepción’s seismic zoning, where in particular the subsoil responds with a natural period of up to 1.7 seconds, aspect that does not happen for buildings toward downtown (east of the Llacolén bridge), although they are still within Zone I. Thus, although there is no geotechnical zoning, without a doubt Zone I of the seismic zoning reflects the presence of less compact or consistent soils, and/or with more thickness than the rest; this last must occur given the presence of mountainous formations to the south of Av. Chacabuco, and to the east of downtown, precisely toward where the soil thickness is reduced.

Figure 3. Provisional metal bridge over collapsed section of bridge over Bío Bío river, Concepción.

Figure 4. Multiple collapsed panels of “old” bridge over Bío Bío river.

Figure 5. O´Higgins Tower, collapsed from tenth floor upwards, at Concepción.

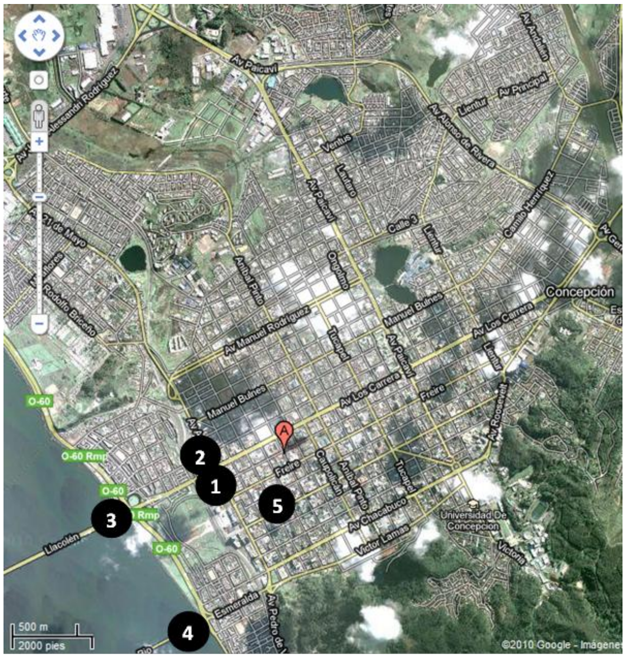

Figure 6. Satellite view of Concepción, Chile (taken from Google, 2010). (Figure numbers are included)

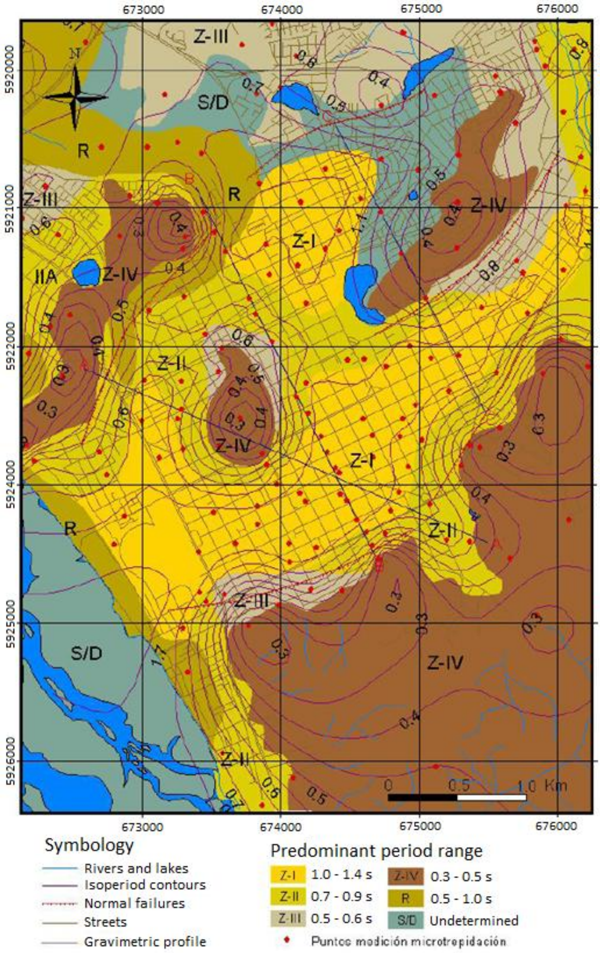

Figure 7. Seismic zoning of Concepción, Chile.

4 ENVIRONMENTAL NOISE MEASUREMENTS

Below are the results of one of the six measurements of environmental seismic noise taken by personnel of the study mission during their stay in Concepción at various sites of the location, soon after the earthquake (II UNAM, 2010). The data provide valuable information that complements the mentioned seismic zoning; the location of the measurements is indicated in each case.

The records of environmental noise presented here, Fig. 8, correspond to the horizontal and orthogonal directions among them, measured on the sidewalk, some 50 meters from O'Higgins tower. Both the amplitude spectra of these records and those obtained from the recording of a replica, Fig. 9, which occurred just as measurements were being recorded, show similar spectral shape, but with different relative amplitude.

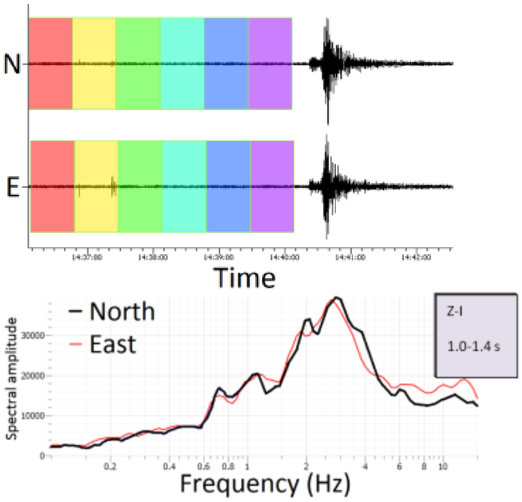

Figure 8. Speeds recorded and spectral amplitudes measured on sidewalk near O'Higgins tower in Concepción, 2010-03-13 (Six windows of 40 seconds each were recorded).

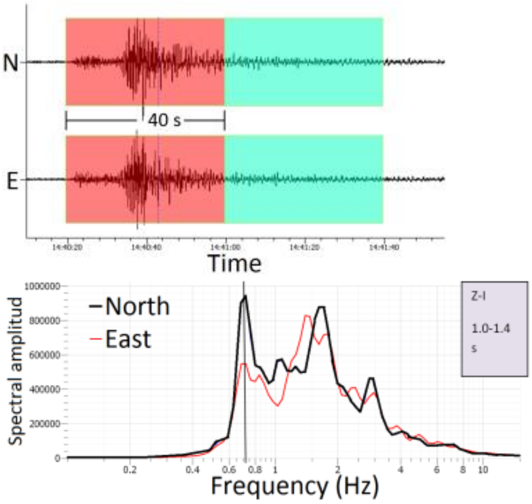

Figure 9. Replica's accelerograms and spectral amplitudes recorded and measured at sidewalk near O'Higgins tower in Concepción, Chile.

The event's spectrum has a very clear spectral maximum on approximately 0.71 Hz, in both components. Also, there are two additional maximums, on approximately 1.4 Hz for the east component and 1.6 for the north component, as well as another one near 3 Hz. The amplitudes associated to the spectral maximums are smaller for increasing frequencies. Both the difference in dominant frequency –certainly significant– associated to the maximum near 1.5 Hz, and the fact that this maximum is not manifested in the noise spectrum, stand out.

5 SAND LIQUEFACTION AND LATERAL SPREADING

Soil liquefaction is a natural phenomenon that is produced in sandy soils, loose or of medium compactness, in saturated condition, when the pore water pressure increases as result of rapid loading processes, such as those induced by seismic movements. The increase of the pore pressure determined the decrease of shear resistance and rigidity, and at the right moment, the total loss of resistance, the soil temporarily behaving like and becoming a viscous fluid under pressure; this last condition determines that upon finding or generating a crack through which the pressure is dissipated, the fluid flows through it dragging the sand with it.

Multiple evidence of the occurrence of the liquefaction phenomenon was observed in an approximate area of up to 350 km from the epicenter. This distance is located within the frontiers established by Ambraseys (1988) for the most distant sites with liquefaction, using data from around the world.

Roads, ports, urbanizations, dwellings, schools, water treatment plants and river banks suffered the effects of liquefaction and lateral spreading; some of these are included here. The lateral spreading phenomenon occurs in combination with liquefaction, when there is a reduced lateral confinement and/or slight slope, lateral movements thus produced, which can reach meters and generate spectacular parallel cracks of great width.

5.1 Roads

Examples of the occurrence of liquefaction on roads are shown in Fig.10, which correspond to Road 5 South from Santiago to Concepción, at the detour to Parral, some 150 km from the epicenter.

The typical pattern is the generation of longitudinal cracks tens of meters long, usually located on the shoulders of embankments no more than one meter high, or else near their middle, and on occasion at the start of slope of small embankments. Dragging, and sand at the bottom of the cracks can be distinguished.

5.2 Urbanizations and dwellings

The commune of San Pedro La Paz is located south of Concepción and on the other side of the Bío Bío river. At a certain urbanization of that town profuse liquefaction of its mid size gray and uniform sands in loose state occurred, Fig. 11, to which an almost superficial phreatic level was added. The sand was dragged not only through the joints of concrete slabs, but also through gardens and garages of single family homes consisting of a ground floor and a second level, causing total and differential sinking, with significant collapse in many homes, Fig. 12.

Even though the liquefaction phenomenon was not by far the main cause of the damage to dwellings, it was reported that this earthquake caused serious damage to, or the destruction of around 200,000 homes, at an approximate cost of USD 4 billion.

Figure 10. Liquefaction on road 5 South, Santiago-Concepción.

5.3 Schools

At another site of the commune of San Pedro La Paz we observed generalized liquefaction at a school of great extension and of relatively recent construction, Fig. 13. It was clear that the light brown mud-sandy surface filling had cracked and allowed the flow of water through and the loss of dark gray sand from underneath, causing settlements of up to 60 cm at the foot of the stairs visible in the photo.

This school serves as an example of the resulting effect in the case of the combination of several relatively light structures with superficial foundations and large open spaces between them. The liquefaction caused profuse cracking over the entire area of the school, with its patios and the neighborhood of buildings. It was significant to distinguish that the pressure on the foundation terrain exercised by one- and two-floor buildings prevented the loss of effective stresses underneath them, determining that liquefaction only occurred a few decimeters from them, developing cracks in the soil parallel to the walls of the buildings, Fig. 14. In no case we observed ground cracking “crossing” under a wall; the rigidity of the buildings contributed to their not cracking. Only in one case we observed relative movement between two bodies of buildings, which caused their fracture.

Figure 11. Generalized liquefaction in a group of single family homes. San Pedro La Paz.

Figure 12. Heavy sinking and collapse in a single family home due to liquefaction.

Figure 13. Liquefaction at a school’s patio in San Pedro La Paz.

5.4 Water treatment plants

The very extensive liquefaction that developed at the commune of San Pedro La Paz even caused the flotation of boxes that constituted the valve room of a treatment plant, as shown in Fig. 15, as well as of an adjacent booth. As in the case of the urbanization’s light homes, the weight of those boxes was not sufficient to prevent the annulment of effective strains in the sandy, saturated and loose ground, generating liquefaction and the flotation of the boxes.

5.5 Cracks on river banks

A marked crack occurred on the left bank of the Bío Bío river, land also belonging to the commune of San Pedro La Paz, on the road to Santa Juana. It developed along hundreds of meters as result of the profuse liquefaction and lateral spreading phenomena, causing multiple damage to homes and restaurants, some not yet opened, that had been built near the river’s border, Fig. 16; the liquefaction phenomenon was even present on the floor inside one of the restaurants, as the result of structuring with very light materials.

Figure 14. Cracking parallel to the school’s constructions, caused by liquefaction. San Pedro La Paz.

Figure 15. Flotation of boxes of a treatment plant in San Pedro La Paz.

Lateral spreading was favored by the slight slope toward the plentiful river, and preceded by liquefaction; the cracks were multiple, with widths of up to a couple of meters, as shown in Fig. 17, and similar depth. These cracks allowed us to witness directly the presence of the layer of mid size and uniform sand of dark gray color, rich in mica, that suffered liquefaction. The sand is the product of the Antuco volcano eruption, and it is located between 1.6 and 1.9 m of depth from the terrain surface, with thickness of 22 cm. We had the opportunity to take samples of the sand to determine its granulometric distribution, finding that it is located just within the zone in which technical literature has defined granuolmetries for liquefaction-prone soils. Over that sandy layer are sandy soils with clay matrix which upon initially encapsulating the sandy layer, propitiated the generation of high pore pressure and therefore liquefaction.


Figure 16. Extended cracking on the bank of the Bío Bío river.


Figure 17. Liquefaction, cracking and lateral spreading on bank of Bío Bío river.

6 BEHAVIOR OF FOUNDATIONS

In general, the behavior of building foundations was satisfactory. It became possible to verify the virtues of a construction consisting of a robust structure supported by a continuous and resistant foundation. Figs. 18 and 19 show the conditions in which a couple of homes built a few tens of meters from the coast of Dichato were left, which suffered the onslaught of the violent tsunami that caused marked undermining. The superstructure, made of confined masonry, had no damage; only the diaphragm that constitutes the front of its roofing, and its windows, showed clear evidence that the water had flowed through them. The foundation formed by continuous footing of a poor concrete proved capable of maintaining the structure whole and with no distortions, even though part of the footing lost its soil support.

Nonetheless, many other constructions showed deficient behavior due to foundation failures, most of the times determined by liquefaction and lateral spreading. In some other cases poor foundation performance was due to frankly inadequate design criteria or decisions, as will be shown further down.

It is clear that the buildings with most damage in their foundations were located in the epicentral zone, precisely where there was a larger development of infrastructure and buildings of mid height; thus, it is not surprising for the damage to be concentrated in the metropolitan area of Concepción, where such conditions exist.


Figure 18. Intact foundation and superstructure of a home that suffered the onslaught of the tsunami in Dichato.

6.1 Alto Río building

With respect to the behavior of its foundation, the Alto Río building that completely overturned in Concepción, Fig. 1, deserves a particular review. The construction had 14 floors and two basements. Fig. 20 shows a longitudinal cut of the building, which had a floor plan proportion of length versus width of 3 to 1. The structure consisted of reinforced concrete walls, typically 20 cm thick, and floor slabs also of reinforced concrete, of 15 cm thickness. The building reached a height of approximately 40 m. The foundation was solved with a solid slab of reinforced concrete 80 cm thick in the area under the tower, set from ground level at -5.94 m, from which the concrete walls rose. In the parking area that was located behind the building, occupying the two basement levels, the foundation slab was 45 cm thick only; both slabs were set over an insole of poor concrete. The finished floor of the second basement slab was located at a level of -5.04 m on both the building and the parking area.

Figure 19. Intact foundation and superstructure of a house that was submitted to the tsunami in Dichato.

The failure occurred when the vertical elements of the ground floor and/or basements collapsed, apparently from compression, on the vertical back plane opposite that of the façade, indicated with an arrow on Figs. 21 and 22. Fig. 22 shows the ground floor plan, indicating the area occupied by the building itself, and the underground parking behind it and out of its projection. Apparently, the reduction or non existence of walls along the longitudinal axis of the building's back façade, indicated with arrows, seems to have propitiated the failure by compression which, in turn, gave origin to the failure by tension of the front façade's vertical elements. The building as a whole overturned with rotation from the ground floor level, the vertical elements of the façade zone failing by tensile rupture, Fig. 23, and therefore the building fell on its back.

Regarding the participation or influence of the foundation in this mechanism, it had been speculated among some local specialists that the building's collapse was due to a foundation failure, probably caused by liquefaction of the underlying sands.

The authors had the opportunity to review the results of geotechnical soundings in which the presence of compact to very compact sand and sandy silt, not susceptible to liquefaction, were detected.

According to the evidence that we could observe during our visit to the site, the foundation did not contribute to the building's overturn, because no indication that it had experimented settlement or rotation was detected. To support this, the image in Fig. 24 shows that the lateral displacements suffered by the foundation box were of very small magnitude, only 6 mm. This means that the continuous concrete wall of the basements on the façade's plane underwent very reduced displacement with respect to the surrounding ground.

Another image that supports the foundation's practical immobility is included in Fig. 25. The bubble is completely level when placing the level on a low wall on the ground floor, indicating that the foundation did not suffer permanent angular distortions. In summary, when the building suffered its overturn, its vertical support elements failed at ground floor level, with the foundation box completely remaining in its original position, with no rotation and with only minuscule lateral displacement.

6.2 Other cases

We inspected other buildings in which, in opposition to the one discussed above, the foundation's characteristics seem to have played a significant role in the deficient behavior of its structure. We do not offer details here of a building of 14 floors, rising in front of the coast line, with marked irregularity on its ground floor plan, height and applied loads. The foundation was solved with continuous and isolated footings rising from a depth of 1.70 m. The discontinuity of the foundation was detected toward one of the ends of the building, zone where the structural damage was concentrated.

7 CONCLUSIONS

One first lesson left by the earthquake that shook the central southern part of Chile on 27 February 2010 is that in spite of its great magnitude and intensity, building collapses were actually reduced, with Chilean engineering meeting its fundamental objective of preserving human lives. It is also true that given the most recent engineering practices, we could observe that the worst damage occurred in relatively modern buildings, and that the loss of housing represents a very high cost for Chilean society. This will surely lead to a review of the Chilean Norm NCh 433 (1996).

In Concepción, as in Santiago or Viña del Mar, the damage was usually associated to its location. In effect, the passing of seismic waves through formations of soft soil of great thickness caused the dynamic amplification of its movements, or site effects.

With respect to the geotechnical aspect, the liquefaction of loose and saturated sandy soils, played the most important role in the behavior of infrastructure and housing, mainly in the lighter ones. Foundations showed good behavior in general, of which it is remarkable those that withstood significant undermining by the tsunami, or else strong overturning moments. Their success was based on having continuous and sufficiently rigid footing. On the contrary, tall buildings whose design was based on superficial and discontinuous foundations also stand out; that aspect seems to have had an influence in their deficient structural performance.

Figure 20. Longitudinal section of Alto Río building.

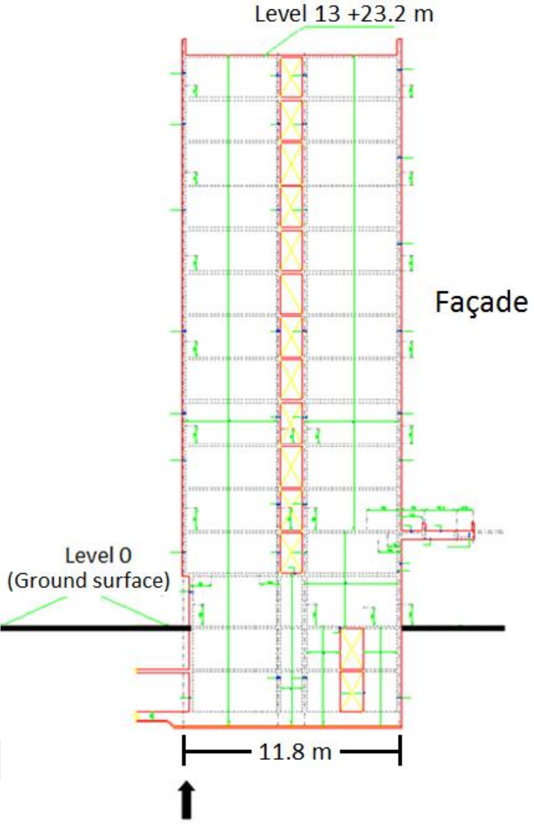

Figure 21. Transversal section of Alto Río building.

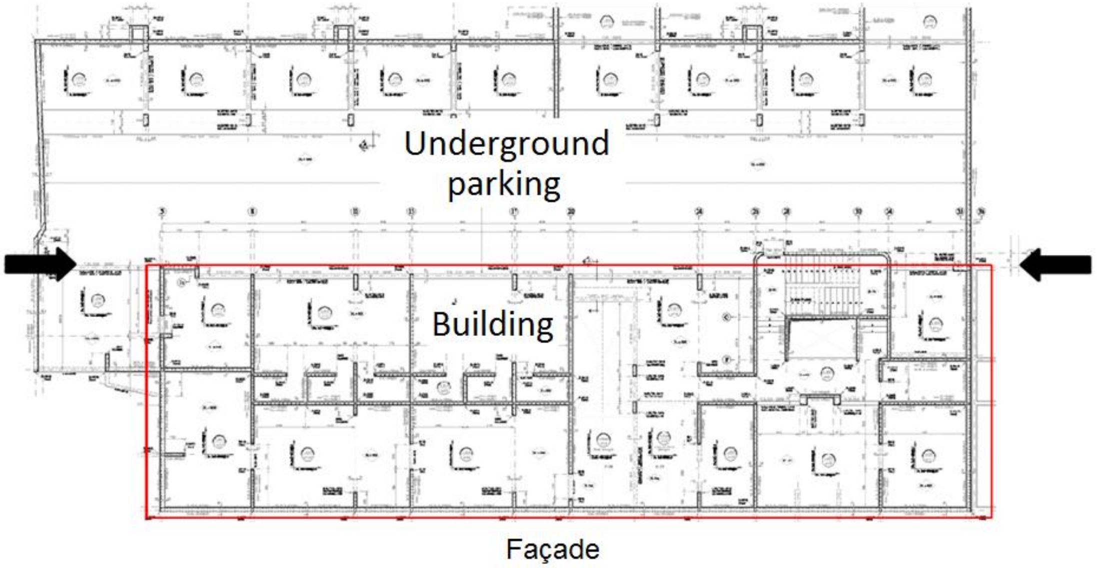

Figure 22. Plan of the first basement of the Alto Río building. Note the scarcity of vertical elements on the longitudinal axis of the building's back façade (arrows).

Figure 23. Final tension failure of the front portion of the ground floor, which determined the building's overturn and collapse.

Figure 24. Lateral displacement of the foundation box of only 6 mm.

Figure 25. Low wall on ground floor totally level after the building's collapse.

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