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DAMAGES OBSERVED IN THE 2010 CONCEPCIÓN EARTHQUAKE RELATED TO SOIL PHENOMENA

Felipe Villalobos [1], Efraín Ovando[2], Manuel Mendoza[3] and Paulo Oróstegui[4]

ABSTRACT

The city of Concepción and surroundings were severely shaken by an earthquake of moment magnitude 8.8 on 27 February 2010. The earthquake hypocenter was located 100 km north of Concepción and 30 km deep. The paper reports soil related phenomena observed in field inspections by the authors. Evidence of liquefaction was observed in places with relatively shallow water table. Liquefaction of poorly compacted granular fills caused tilting of sewage buried tank systems and differential settlement of houses, school buildings and some industrial installations. Lateral spreading was observed along river banks and around swamps and it was also visible along the main motorway, Ruta 5. This phenomenon caused large deformations in the soil resulting in significant destruction. Analyses of cases and recommendations to mitigate the damages described are suggested. The phenomenon of tsunami scour was observed in houses in front of the shore, removing soil underneath footings. Further studies to determine the extension of this type of scour are required.

Keywords: Concepción 2010 earthquake, liquefaction, lateral spreading, tsunami scour

INTRODUCTION

On 27th February 2010, an earthquake of moment magnitude 8.8 occurred at 3.34 am (local time), with the hypocentre located at a depth of 30 km and 100 km north of Concepción, at latitude 36.29ºS and longitude 73.239ºW (Seismologic Service University of Chile 2010). The main quake had a duration of 90 s and extended 450 km from Tirúa in the south to Valparaíso in the north covering a width of approximately 150 km. Relative displacements between Nazca plate and South American plate were of the order of 10 m with maximum values of 12 and 14 m. More than three hundreds aftershocks occurred, the majority above magnitude 5 Richter and more than 20 equal or above 6 Richter. Acceleration measurements in San Pedro de la Paz (Colegio Concepción) show values in the order of 0.5g. The peak acceleration recorded reached 0.65g N-S. Therefore, the earthquake magnitude, the duration and the accelerations recorded correspond to an event of significant characteristics to be studied. For more information about this earthquake see for example Barrientos (2010).

Concepción and its surroundings form the Greater Concepción, including among other towns Penco, Talcahuano, Hualpén, San Pedro de la Paz and Chiguayante. Greater Concepción is an important historical, cultural, commercial and industrial centre located on the coast of the Bío Bío Region, where the Bío Bío River flows into the Ocean Pacific. Concepción was originally founded in 1550 where is today the town of Penco. However, after several destructives earthquakes and tsunamis (1570, 1657,

[1] Lecturer, Dept. of Civil Engineering, Catholic University of Concepción, Chile, avillalobos@ucsc.cl
[2] Professor, Engineering Institute, UNAM, México, eovs@pumas.ii.unam.mx
[3] Professor, Engineering Institute, UNAM, México, mjm@pumas.ii.unam.mx
[4] Geotechnical Engineer, Constructora Lancuyen Ltda., Concepción, Chile, orostegui@lancuyen.cl

1687, 1730 and 1751), it was decided to move from Penco to the Mocha Valley, the current place of Concepción, 5 km inland, near to the Bío Bío River and the Caracol Hill. It is also worth mentioning the later big earthquake of 1835, reported by Darwin (1845) as a witness of the aftermath, the Chillán earthquake of 1939 which also caused considerable destruction in Concepción and the earthquake of 1960, the largest ever recorded earthquake in the world.

This paper describes the particular soil conditions which may have influenced the response of foundations of damaged buildings, bridges, harbours and silos. Geotechnical and seismic zonification studies of the area are scarce. Gutiérrez (1991) studied the amplification phenomenon modelling the subsoil from the bedrock to the surface for Talcahuano and Concepción. He used the software SHAKE and 1985 earthquake acceleration records from Viña del Mar (a_{max} = 0.3g, mean frequency of 2.2Hz) and Valparaíso (a_{max} = 0.15g, mean frequency of 5.6Hz) as inputs since no recordings for Concepción were available. It was concluded that, for these inputs, in the centre of Concepción and Talcahuano there is an acceleration amplification of no more than 50% for the top 20 m. However, deformation amplification of soft silt layers can be up to four times larger than that for sand layers. Recently Ramírez and Vivallos (2009) have presented a geological map showing soil and rock fundamental periods of vibration in the city of Concepción (Figure 1b). Six zones are identified according to the dominant period, gravimetry (bedrock depth) and geology (soil deposit and rock type). The paper focuses on cases where evidence of damage on structures was observed, especially related to the phenomena of liquefaction, lateral spreading and tsunami scour.

GEOLOGICAL AND GEOTECHNICAL CONDITIONS

The geological and geotechnical conditions in the studied area are complex because of the presence of several features, units and spatial variations. Briefly, the main features in the zone are the presence of hills, recent soil deposits and water bodies as lagoons, rivers and swamps. The higher hills form the coastal mountain chain, *e.g.* Lo Pequén, Caracol and Andalué. There are also several hills isolated emerging (island hills), between the higher coastal mountains and the shore such as Chacabuco, Amarillo, La Pólvora, Lo Galindo and Chepe. These mountains and hills are composed by metamorphic and igneous rock units belonging to Palaeozoic eras. In Figure 1a metamorphic rocks such as schist and phyllite are represented by the legend SE (diagonal lines symbol). Igneous rocks, *e.g.* tonalite, granite and granodiorite, are shown by the legend Pzg (X symbol). There are also sedimentary rocks from Eocene, a more recent geological time, in the form sandstones and siltstones with presence of coal, shown by the legend Ec (square symbol) belonging to the Curanilahue formation. The legend Kq (little stone symbol) refers to the Quiriquina formation, another sedimentary unit with sandstones and conglomerate. Sedimentary rocks can be found lying with a certain angle on metamorphic rocks or both can be intruded by igneous rocks too. The older rocks are the result of high tectonic activity and the presence of old and hidden non active normal faults. A common feature is the high level of weathering, a chemical and physical phenomenon that decomposes the rock mainly due to the presence of water coming from persistent rain and also by salty air. A granite rock can be weathered from the surface as deep as 50 m.

Transport of river sediments and material sliding and rolling from hills and mountains have deposited material within basins originally submerged under the sea. Figure 1a shows the legend PIHstm (dots symbol) representing widespread sediments of marine terraces. There is also presence of sediments of fluvial terraces, in Chiguyante for example. Bío Bío River, one of the longest and largest of the country, has been continuously depositing basaltic sand carried from the Andes around the mouth area before and after the retreat of the sea. The Bío Bío sand is in general clean, *i.e.* without fines content and uniformly distributed, although it can be found mixed with silts deposited by the Andalién River or with soils resulting from weathered rocks. For more geological information see Galli and Lemke (1965) and Quezada (1995).

Figure 1b shows the results of a work carried out by Ramírez and Vivallos (2009), where lines of equal soil period of fundamental vibration are traced. The gravimetric information was calibrated with results from a borehole, in the centre of Concepción, of 133 m depth which touched the basal rock. An interesting aspect of this work is that periods of the soil can be related to the ground type or condition. For example, periods between 0.3 and 0.5 s correspond to rocky hills and periods between 0.7 and 1.4 s correspond to sandy and silty deposits, where a particular value is a function of the material density or compactness. This information is very useful for instance to understand site effects phenomena like amplification or attenuation. Figure 1b also shows some lagoons and parts of the Bío Bío and Andalién Rivers. Around these water bodies soils are generally poor because of saturated, loose, soft or organic deposits forming swamps. It is important to point out that the Bío Bío River flowed as a delta towards the bays of Concepción and San Vicente as well as towards the current direction, *i.e.* Arauco Gulf, leaving several lagoons and wetlands which were part of old arms of the delta.

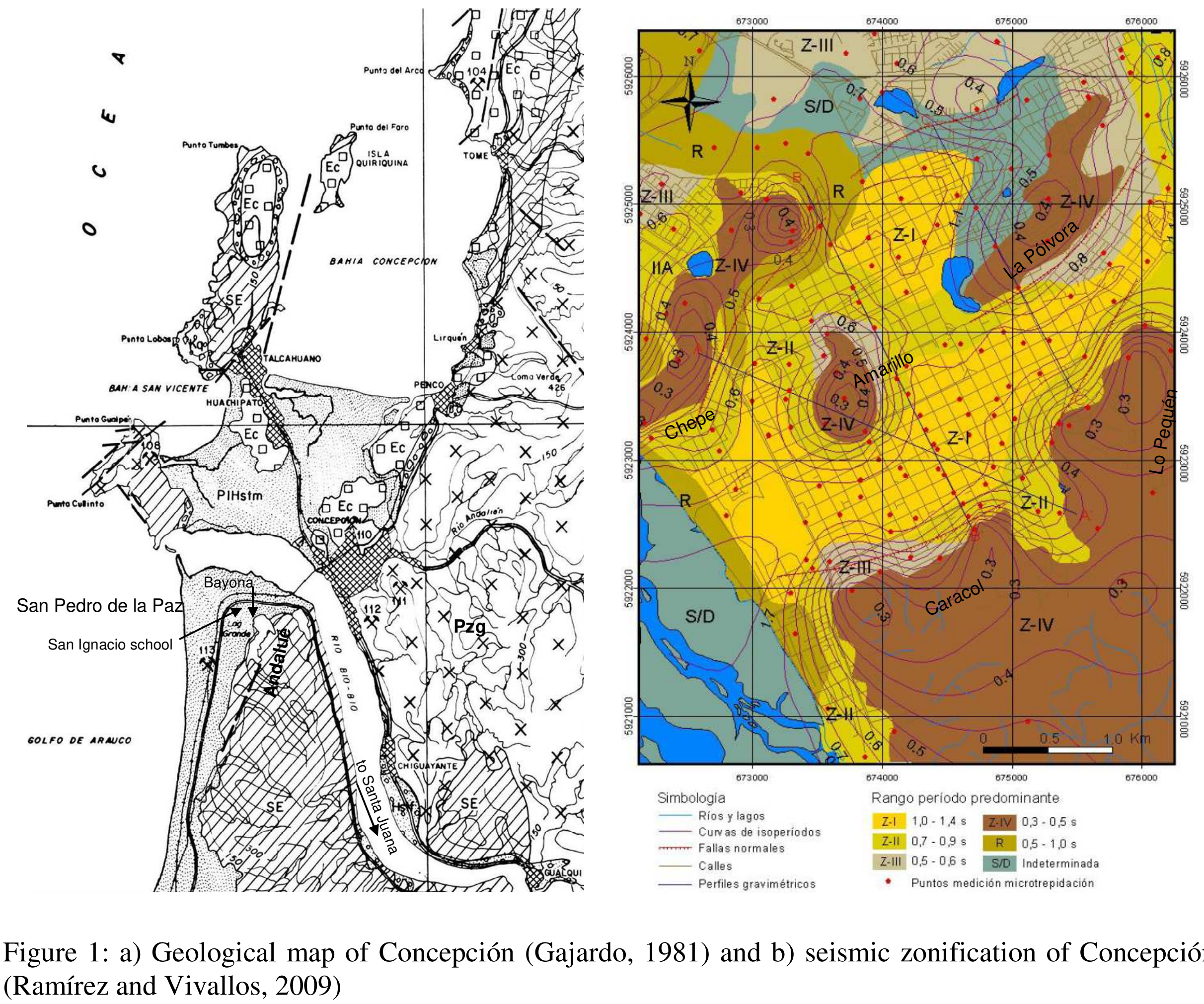

Figure 1: a) Geological map of Concepción (Gajardo, 1981) and b) seismic zonification of Concepción (Ramírez and Vivallos, 2009)

COLLAPSED STRUCTURES

In Figure 2 circles with numbers indicate the place of collapsed structures. It has been tempting to directly blame the subsoil as the main reason of these and other failures. Circle 1 refers to the apartment building Alto Río, a two years old reinforced concrete building of 12 to 15 floors and two basements, 3:1 length and width ratio in plant, walls and slab thickness of 20 cm and 15 cm respectively. This building corresponded to the first of four similar but not attached buildings projected in this corner. The building is founded on a reinforced concrete box (the two basements), through which loads are transfer to the subsoil by a 80 cm thick slab 6 m below the surface. From the slab the building columns, shear and retaining walls arise. The soil profile consists of medium to dense Bío Bío sand deposits with layers of soft silt, having a water table from 3 to 4 m deep. Particular concern was the presence of two non plastic silt layers between 9 to 11 m deep and between 12 to 17 m deep, with values of deformation modulus E_u of 20 MPa and 30 MPa and undrained shear resistance s_u of 150 kPa and 300 kPa respectively. These values were obtained from undrained triaxial tests after applying 30 loading cycles with a constant deviator stress of 90 kPa and confining stress of 130 kPa. The silt samples underwent excess pore pressures of no more than 95 kPa accumulated at the end of the cyclic loading. No stiffness degradation was found hence no liquefaction occurrence (Petrus 2006).

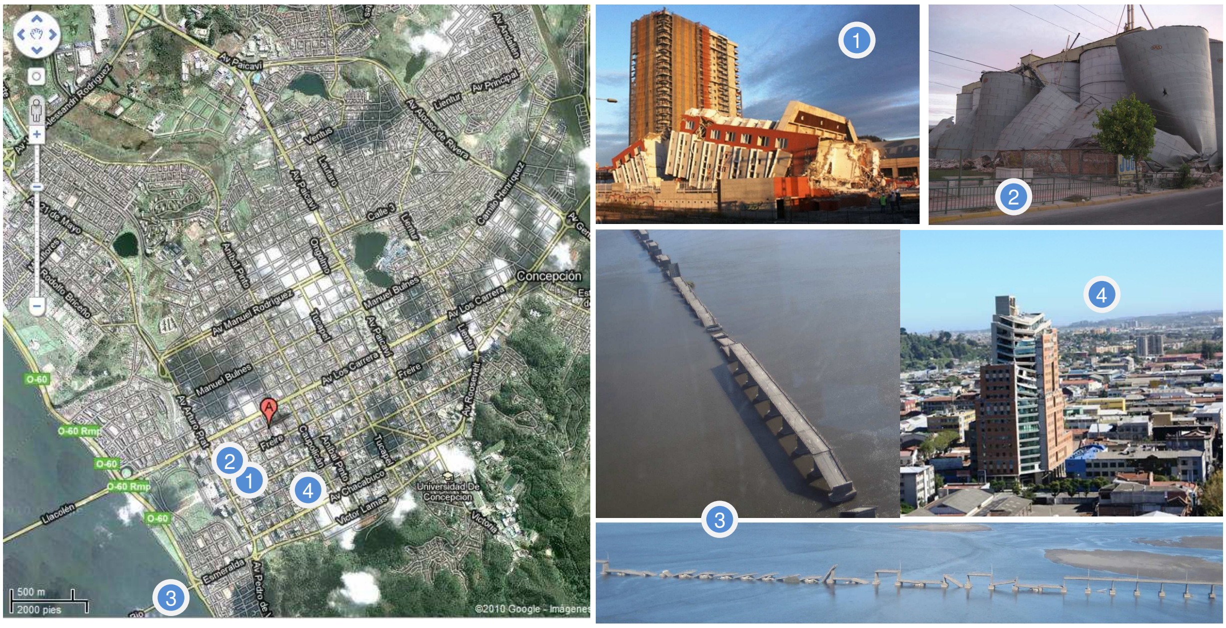

Figure 2: Satellite view of Concepción showing location and pictures of collapsed structures

It is worth mentioning that the tower had a significant eccentricity respect to the basement since the basement extends backwards beyond the boundaries in plant of the tower (Figures 3a and 3b). Openings through the walls allowed the access to the extending basement area (Figure 3b). This gave origin to a weak line exactly at the back of the building. Witnesses indicate that the tower swung torsionally and then sunk at the back and finally the columns and shear walls in the front line were cut at the ground level to fall backwards completely after no more than 30 s from the beginning of the earthquake. The authors inspected the site and could not find serious evidence of settlement, lateral displacement (6 mm), rotation or any bulge indicating the development of a soil failure mechanisms, nor evidence of liquefaction or geological fault. Nevertheless, studies of amplification need to be carried out to find out whether accelerations and deformations were particularly high due to the presence of the soft silt layers.

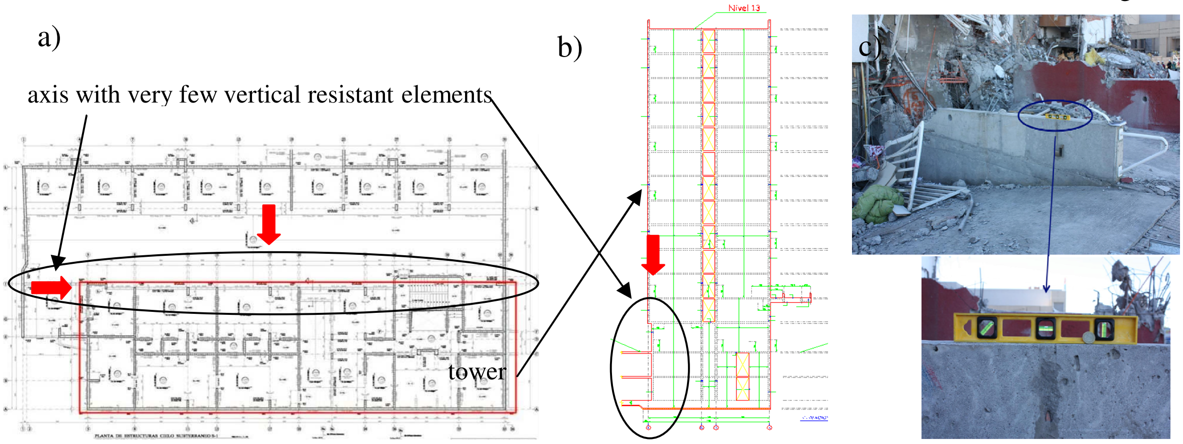

Figure 3: Alto Río a) tower in an eccentric position respect to the whole basement, b) openings at the back where failure may have started and c) base without tilting

Circle 2 corresponds to two rows of wheat silos located to less than 100 m from Alto Río building. For that reason soil profiles and conditions can be assume as similar as in Alto Río. The first row of silos was built in the 50's and did not present damage (Figure 2b). The second row was built during the 70's and collapsed due to the failure of bolts connecting the steel silos to the footings. According to witnesses full silos burst at the based spreading wheat. The shaking densified the granular content increasing vertical stresses and therefore radial stresses as well at the base, stresses which the silo steel shell could not withstand. The authors did not find any evidence of soil failure mechanism in situ.

Circle 3 shows the old Bío Bío Bridge built during the 40s and also collapsing in the 1960 earthquake (Steinbrugge and Flores 1963; Duke and Leeds 1963). In the 60's only a couple of piers failed on the Concepción side. Due to lack of maintenance the bridge was abandoned and hence without use since 2003. In the 2010 earthquake a generalised domino effect of pier failure occurred not only on the Concepción side but also on the San Pedro de la Paz and in the middle of the bridge. It is not clear whether the bridge timber pile foundations failed or not due to, for instance, liquefaction. Liquefaction was observed downstream in the river sand banks. It has been speculated that geological faults run along the river and also cross the river exactly there, because the Caracol hill would continue on the other side in San Pedro de la Paz. Therefore, geological studies are required in the form of geophysics and gravimetric analysis for example.

Circle 4 represents the collapse of the top 10 floors of the 21 floors O'Higgings Tower. Between the 11th and the 12th floor a discontinuity in the structure triggered the collapse of structural members which in turn failed the building upwards. The authors did not find any evidence of soil failure around the tower.

Further studies need to be pursued to whether these collapses are purely related to deficiencies in structural design and construction materials and methods or there are geological and geotechnical issues such as acceleration and displacement amplification due to for example soft soil layers just under these particular sites.

DAMAGE DUE TO LIQUEFACTION AND LATERAL SPREADING

Liquefaction is a natural phenomenon which occurs mainly in loose saturated sandy soils when the excess pore pressure increases as a consequence of rapid loading such as those induced by seismic movements. This increase of excess pore pressure during each loading cycle can result in a significant reduction of the soil shear resistance. As a consequence the soil stiffness strongly decreases. The soil failure due to liquefactions induces large displacements and structures resting on a liquefied soil can suffer considerable damage. The authors observed evidence of this phenomenon in the form of, among others, cracks expelling saturated fine material where excess pore pressure was dissipated. The furthest sites where liquefaction was observed were in the motorway Ruta 5 Sur leaving Santiago, around 350 km from the epicentre. This distance is within the range proposed by Ambraseys (1988), as a function of the earthquake magnitude, for most distant sites where liquefaction has occurred worldwide (Figure 4).

Effects of liquefaction and lateral spreading caused serious damage to embankments of motorways, developments, wharves, schools, sewage plants and constructions on reclaimed land. Lateral spreading can occur in combination with liquefaction when lateral confinement is reduced even in a smooth slope, particularly in cases when the slope ends at the toe in a water body, i.e. river, lake or wetland. Large lateral movements can generate impressive cracks on the ground. The main motorway between the South and Santiago had several examples of longitudinal ground cracks in saturated low land areas breaking mostly shoulders and sinking dual carriageways. Drainage should be improved evacuating water out from the subsoil through deep longitudinal channels or using wells.

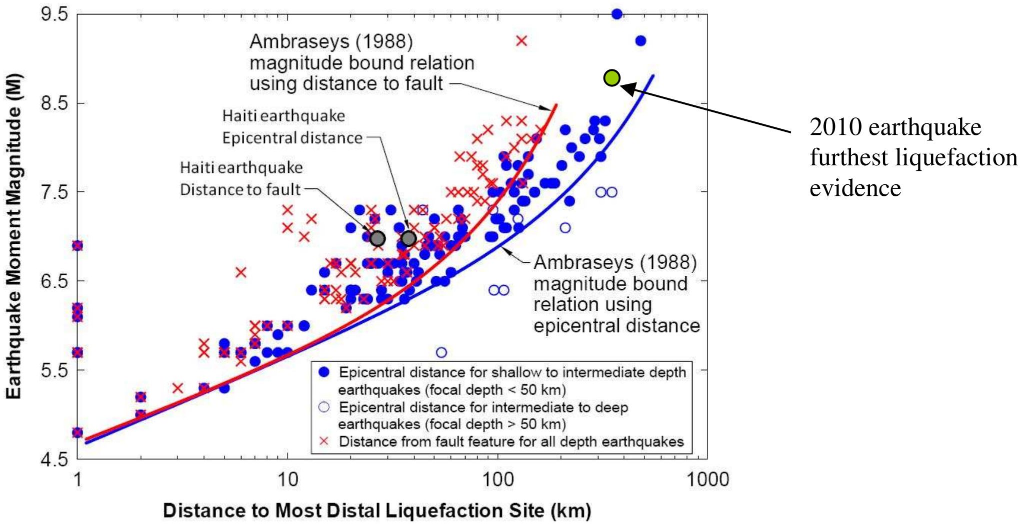

Figure 4**:** Maximum distances for occurrence of liquefaction as a function of earthquake magnitude (Ambraseys, 1988)

San Pedro de la Paz

A group of houses in the neighbourhood of Bayona in San Pedro de la Paz, near to *Laguna Grande* and built in the middle 90s, suffered damage due to ground settlement. Houses are located in a transition from the lap of a hill (residual soils) to a lower ground originally part of Los Batros swamp. The houses damaged were in the lower ground where soil is saturated and probably it was not well compacted. Evidence of fine material flowing to the surface through concrete joints in garden pavements and in garages was observed. Yasuda *et al.* (2010) report a house maximum total settlement of 17 cm. Moreover, differential settlements caused rotation of some houses and bulging deformation of the ground floor. Soil improvement should be considered under the house footings to increase seismic bearing capacity and avoid liquefaction.

The school of San Ignacio in San Pedro de la Paz, with the same subsoil of Los Batros swamp did not suffered noticeable damage in its new facilities except ground settlements around playgrounds up to 60 cm and in an isolated one floor building, close to the swamp (see Figure 5). This rectangular reinforced concrete building of 15 m wide and 40 m long is founded on shallow footings 1.1 m below the surface with the water table between 1 and 2 m deep. Soil mechanics studies indicated that the subsoil had too poor quality to found the school. Therefore, a soil improvement was considered by using biaxial geogrids and geotextiles under compacted 80% relative density clean Bío Bío sand of 3 m thickness below the foundation level to replace a compressible silt (Sepúlveda, 2006). The only building with structural damage had to cope with ground displacement towards the swamp. The damage concentrated in a singularity of the building architecture, which could not keep the ground movement. This singularity corresponds to a separated room slightly offset from the rest of the structure, with a different roof level and on one side without solid structural connections with the main structure. As a consequence this room tilted 4º, hence openings cracks of 10 cm wide on the floor and detaching from the roof and windows. It is worth mentioning that the authors are not aware to whether the geosynthetic solution was applied on the whole area or only under some facilities. In the light of the observed cracks in the soil and in the building, it is believed that a confinement deficiency occurred towards the swamp. A natural slope exists towards the swamp and despite the compacted and reinforced sand fill, the land level at this point is approximately 1 m lower than for rest of the area. Possible solutions are to build a retaining structure or to extend the ground improvement further than the existing 8 m to the swamp.

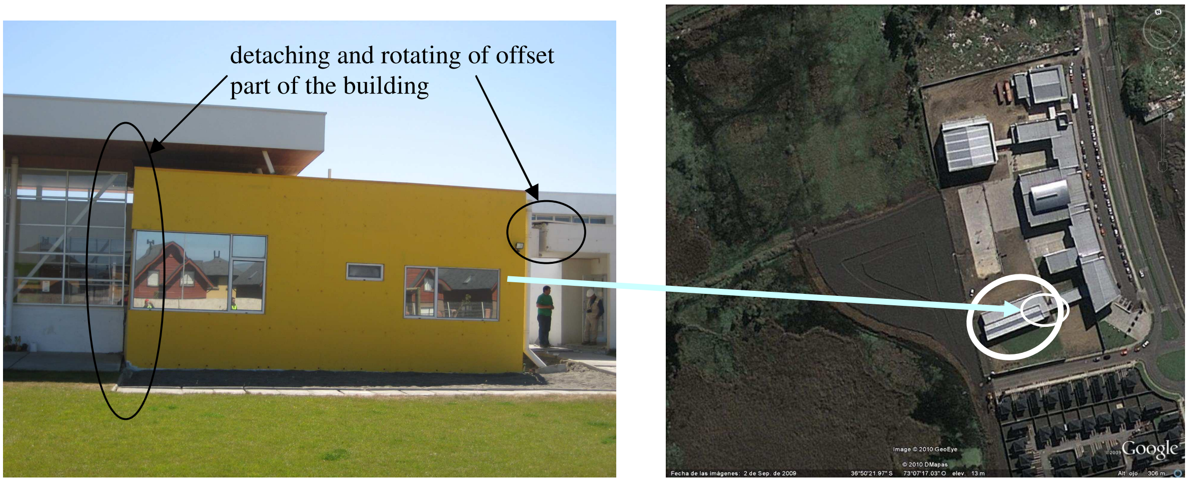

Figure 5: San Ignacio School, San Pedro de la Paz showing where damage was concentrated

Striking crack patterns were observed along the Bío Bío River south bank also in San Pedro de la Paz, along the road to Santa Juana. Along hundreds of meters these cracks developed parallel to the river, causing serious damage to structures. A cross section sketch would show hills of 100 m on one side of the road and then a narrow land ending into the river. This narrow piece of land (50 to 100 m wide) has been reclaimed mostly with material from the hill and also from the river to avoid flooding. The authors are not aware of any type of soil improvement carried out to reclaimed ground, except under the road and under some structures closer to the road. Ground movement towards the river was considerable, destroying restaurants, houses, swimming pools, piping and gardens (Figure 6). It is believed that liquefaction occurred in deposits of saturated and loose sand below 2 and 3 m from the surface, at the level of the river (Figure 7). Above that level, reclaimed ground slid on the liquefied sand towards the river. Sand deposits were trapped, unable to dissipate excess pore pressures, since reclaimed grounds were residual soils from weathered rocks in the form of silt and clay material. Some cracks closer to the river had depths of 2 m and 1 m wide. Without intensive improvement of the natural soil deposited by the river and the soil fill deposited by the man it is not recommended to found structures, otherwise large soil displacements occur due to lateral spreading.

Figure 6: Damage in a restaurant, garden and piping due to lateral spreading along Santa Juana road

A sewage plant located between Bayona and San Ignacio School was also on ground reclaimed to Los Batros swamp. Two buried tanks (of three) floated, uplifted around 1 m and tilted 15º due to soil liquefaction. These two tanks of approximately 3 m diameter and 7 m deep had steel pipes connections broken. But soon after the earthquake the plant was working again using extension pipes with angles to accommodate the tilted, uplifted and twisted new tank geometry. There were also manholes near the sewage plant uplifted no more than 30 cm from the road surface. To find solutions to this problem it is necessary to do research about buried structures prone to uplifting due to liquefaction. Perhaps ground improvement alone is not enough and these type of structures need to be anchored.

Figure 7: Sand found at crack bottom with grain size distribution inside highly liquefiable range

Harbours and industrial facilities

An important industrial hub of the country is located in San Vicente Bay, Talcahuano. There, since 1950 is located Huachipato, a plant of the Pacific Steel Company CAP. This plant had to stop production as a consequence of serious damage in its two blast furnaces and other facilities such as piping, containers of raw materials, conveyors and wharf. In the 1960 earthquake the plant underwent also damage, but did not stop production. For a structural point of view of CAP damages see Vignola and Arze (1960) and Blume (1963). Only the second and fourth authors have inspected the plant. Soils present in the site are mostly well graded sands with little silt which are marine deposits and also sediments carried by the Bío Bío River. There are also artificial fills and with depth sandstones, clays and coal can be found. Liquefaction occurred only in a few places, for example in two reinforced concrete sedimentation ponds of dirty water 20 m wide, 40 m long and 4 m deep, parallel to the shore line. Liquefied soil uplifted both ponds. Soil cracks with material ejected from below were observed in between both ponds. Liquefaction on one extreme of these ponds affected a corner of a neighbour building of electrical equipments, inducing settlement under a column.

The plant's wharf was built in 1945 and extended in 1972 to the current 400 m long. The first part is founded on pre-concreted piles of 50 cm square section and reaching depths between 15 and 18 m. There is a high pile density including inclined piles to resist horizontal loads (Figure 8a). The 1972 extension rests on driven steel tubular piles 457 mm diameter and 20 mm thickness and filled with in situ poured concrete. Additionally, these piles have an external annular concrete cover of 25 mm thickness where 12 mm steel bars were in contact along the steel tube becoming pile reinforcement as well (Figure 8c).

In the wharf's access embankment settlements and lateral displacements were observed in the form of a step. Apparently pre-cast concrete piles of the 1945 part did not experience damage, although it was discovered that reinforcing elements inside the piles are in an advanced state of corrosion since they crumble easily when touched by hand. Therefore it is necessary to repair or replace as soon as possible corroded steel elements which reduce the structure resistance. In addition, several pile caps of the 1972 extension failed and a portal crane on the wharf's platform tilted because wheels on one side derailed. In these peculiarly designed piles, the welded connections to the platform were cut. These joints require stronger connection elements to withstand large seismic forces transmitted back and forth from the piles to the platform. It is not recommended to joint two stiff and heavy elements (group of piles with the platform) without a well reinforced pile cap.

Figure 8: a) Piled foundation of the wharf, b) portal carne derailed, c) pile cap broken in wharf extension and d) wharf general view

FOUNDATIONS SCOURED BY TSUNAMI

After the earthquake there was a series of tsunamis flooding some parts of the coastal area depending on the position and distance respect to the epicenter, bathymetry and topography. The seaside town of Dichato was one of the most devastated places along the coast. Several waves swept away the lower parts of the town hitting the front and the back of the town because waves entered through a stream. Dichato is located 9 km north of Tomé in the close and small bay of Coliumo. The bay shape probably caused intense rebound of currents. The few houses standing after the tsunami were made of reinforced concrete or bricks or a mixed of both. However, the authors noticed that standing houses in front of the shore had part of their foundations exposed. The tsunami attacked four or five times according to witnesses being the third and last wave the highest. High velocities and therefore large drag forces were imposed by the tsunami current when arriving as well as when retreating. The tsunami strong currents scoured the footing of the few standing houses. Figure 9 shows a house in cantilever, resting on one side since the other side was removed by tsunami currents. It is worth remembering that this house resisted a strong earthquake and a devastating tsunami. For future constructions on the shore it should be considered structures in addition to earthquake and tsunami resistant also the effect of scour. This phenomenon form normally part of bridge design for example or in structures under strong sea or river currents. A possible solution is to deepen the foundation to a depth where scour does not remove the foundation soil. The scour needs to be calculated with hydraulics methods.

Figure 9: A house in Dichato with foundation exposed due to scour by tsunami

CONCLUSIONS AND RECOMMENDATIONS

Failure and associated damages are normally not caused by only one reason. The extremely strong seismic event plus a combination and succession of several shortcomings and defects led to failures observed during the 2010 earthquake. Some of these cases are presented, described and analysed in this paper. When necessary, solutions are recommended.

In particularly damaged areas it is recommended to perform research focusing on the phenomenon of amplification due to the presence of soft soil layers inserted in between sand deposits or when soil deposits are not horizontal or the bedrock is shallow or inclined (close to a hill for example). The aim is to find out whether accelerations and displacements reaching structures on the surface are much higher or not than those occurring in deep horizontal deposits without soft silt layers. In addition, geological research is necessary to determine the existence and position of faults, for example along the Bío Bío River or exactly where the new Chacabuco Bridge has been proposed next to the collapsed bridge.

Studies considering geophysics, gravimetric analysis and involving borehole campaigns should be considered.

In general, drainage conditions should be always taken into account for the good performance of roads and motorways and especially for the case of dissipating seismic induced excess pore pressures inside the soil foundation.

Diverse soil improvement technique should be considered for possible solution when soils present poor quality and deep foundation are considered too costly. Architectural designs with singularities combined with structural solutions unable to resist stress concentrations due to these singularities led to poor performance. In addition to lateral spreading occurrence owing to a not constrained corner next to soft soil deposits despite the use of dense and reinforced sandy soil.

REFERENCES

Ambraseys, N. (1988). Engineering seismology. *Journal of Earthquake Engineering and Structural Dynamics* **17**(1), 1-105

Barrientos, S. (2010). Terremoto Cauquenes 27 febrero 2010. Updated technical report 27 May 2010. Seismologic Service University of Chile (2010). http://ssn.dgf.uchile.cl/

Blume, J. (1963). A structural dynamic analysis of steel plant structures subjected to the May 1960 Chilean earthquakes. *Bulletin of the Seismological Society of America* **53** (2), 439-480

Darwin, Ch. (1845). *The voyage of the Beagle*. Wordsworth classics of world literature, Hertfordshire

Duke, M. and Leeds, D. (1963). Response of soils, foundations and earth structures to the Chilean earthquakes of 1960. *Bulletin of the Seismological Society of America* **53**(2), 309-357

Gajardo, A. (1981). Avance geológico, hoja Concepción-Chillán, Región del Bío Bío. Instituto de Investigaciones Geológicas, Santiago

Galli, C. and Lemke, R. (1965). Mapa del suelo de fundación de Concepción. Instituto de Investigaciones Geológicas, Santiago

Gutiérrez, A. (1991). Las propiedades dinámicas de los suelos y su respuesta sísmica. *Revista de Ingeniería Universidad de Concepción* **3**(1), 37-46

Petrus (2006). Informe de Mecánica de Suelos, edificios Avdas. Los Carrera-Padre Hurtado, Concepción. Internal report

Quezada, F. (1995). Geología urbana y ambiental de la ciudad de Concepción. Memoria para optar al título de Geólogo, Universidad de Concepción

Ramírez, P. and Vivallo, J. (2009). Microzonificación sísmica de la ciudad de Concepción – Chile. XII Chilean Geological Conference, Congreso Geológico Chileno, Santiago

Seismologic Service University of Chile (2010). http://ssn.dgf.uchile.cl/

Sepúlveda, L. (2006). Informe mecánica de suelos – construcción Colegio San Ignacio, San Pedro de la Paz. Internal report

Steinbrugge, K.V. and Flores, R. (1963). The Chilean earthquake of May, 1960: a structural engineering viewpoint. *Bulletin of the Seismological Society of America* **53**(2), 225-307

Vignola, P. and Arze, E. (1960). Behaviour of a steel plant under major earthquakes. *Proceedings of the Second World Conference on Earthquake Engineering*, Tokyo, Vol. 1, 555-579

Yasuda, S., Verdugo, R., Konagai, K., Sugano, T., Villalobos, F., Okamura, M., Tobita, T., Torres, A. and Towhata, I. (2010). Geotechnical damaged caused by the 2010 Maule, Chile earthquake. ISSMGE Bulletin 4(2), 16-27