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COMPARING LIQUEFACTION PHENOMENA OBSERVED DURING THE 2010 MAULE, CHILE EARTHQUAKE AND 2011 GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT: On February 27, 2010, the central-south part of Chile was affected by a strong ground motion of Magnitude 8.8, that induced moderate values of peak ground acceleration (PGA) on rock outcrops, in the range of 0.13g to 0.32g, while in soil deposits, a maximum PGA of 0.94g was recorded. The duration of the shaking was close to two minutes as it is substantiated by the available acceleration records. A significant number of sites experienced the phenomenon of liquefaction, causing failures of houses, buildings, bridges, routes, ports, railways, buried structures and tailings dams. Likewise, widely spread soil liquefaction was also observed during the 2011 Great East Japan Earthquake. The ground motions of this earthquake and the subsequent aftershocks also had long duration. In this paper, the effects of durations of seismic shaking on the liquefaction-induced damages are highlighted, and compared between the 2010 Chile earthquake and the 2011 Japan earthquake. Especially, the damages induced by liquefaction observed in bridges and ports in Chile are presented and analyzed. Additionally, several cases of lateral spreading observed along rivers and lakes are presented.

Key Words: Maule Chile earthquake, Great East Japan earthquake, Liquefaction.

INTRODUCTION

A mega earthquake of Magnitude 8.8 occurred in the South-Central part of Chile on February 27, 2010, at 3:34 a.m. local time. A significant number of aftershocks followed the initial quake. The most important, Magnitude 6.2, occurred 20 minutes after the main shock (USGS, 2012). The earthquake triggered a tsunami that struck off the Chilean coast, devastating towns located onshore, causing additional deaths and widespread damages. The 2010 Maule Chile earthquake is associated with the subductive seismic environment generated by the collision between the Nazca and the South American tectonic plates, which are converging at an estimated rate of 65 to 80 mm per year. The Nazca plate is subducting under the South American plate, moving down and landward. The Maule Earthquake has been identified as a thrust-faulting type that occurred on the interface between these two plates, at an average depth of 30 km. The rupture zone involved in this earthquake can be observed in Fig. 1, which dimensions cover a rectangular area of approximately 450 km by 170 km. The earthquake together with the tsunami caused near 600 casualties and an estimated economic loss of 30 billion US dollars.

On Friday, 11 March 2011, at 14:46 local time, a mega earthquake of Magnitude 9.0 hit the northeast coast of Honshu, Japan. After a few minutes a series of large aftershocks of Magnitudes of 7.4, 6.4, 6.1, 7.4 and 7.2 struck the area at 15:09, 15:06, 15:13, 15:15 and 15:26, respectively (K-Net, 2012). The main shake was followed, approximately after 20 minutes, by a huge tsunami that destroyed many cities along the Pacific coast. This earthquake, known as the 2011 Tohoku earthquake, or the Great East Japan Earthquake, resulted from thrust faulting on, or near, the subduction zone plate boundary between the Pacific and North America plates. In the area of the earthquake, the Pacific plate moves approximately westwards with respect to the North America plate, at a rate of around 80 mm per year. Models of the rupture zone indicate that the fault moved upwards around 40 m, and slipped over an area approximately of 500 km long by 200 km wide (Fig. 1). The rupture zone is roughly centered on the earthquake epicenter along-strike. This strong ground motion left more than 15 thousands people dead, and even more imperiled, and an estimated total economic loss of 300 billion US dollars.

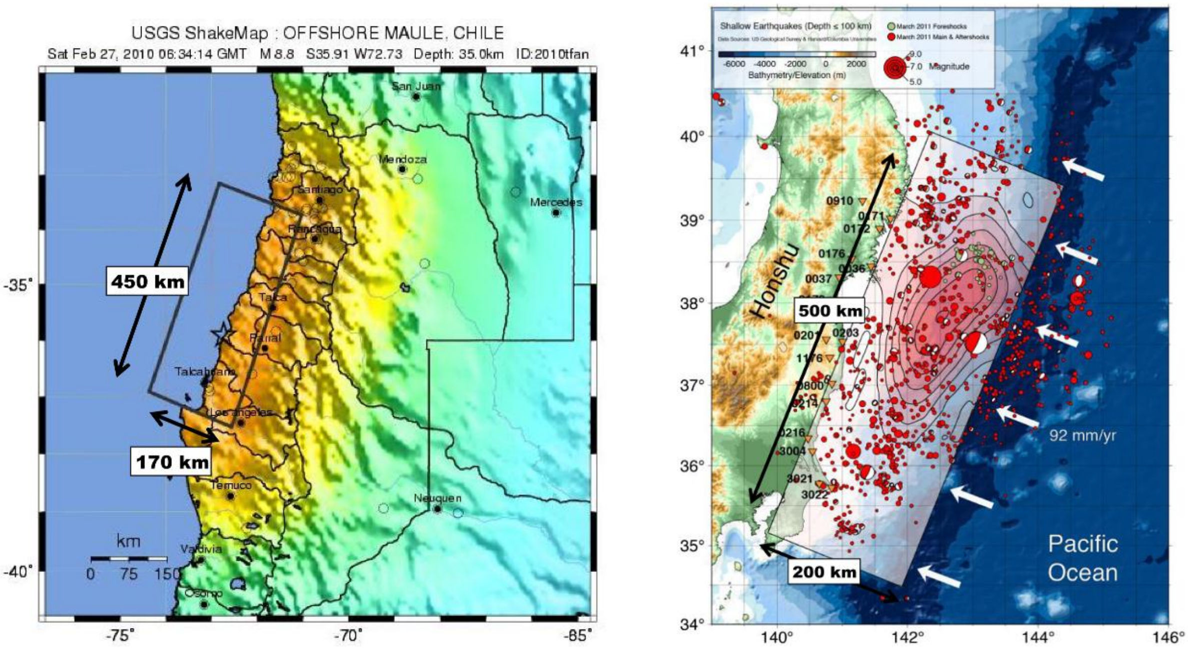

Fig. 1.- Rupture zones associated with Maule (USGS) and Tohoku (Ammon et al, 2011) earthquakes

As can be observed, strong earthquakes with magnitudes above 8.5 develop huge areas of rupture, compromising hundreds of kilometers, with the corresponding generation of seismic waves. Therefore, the usual characterization of the epicenter by a single point does not represent the actual phenomenon of seismic energy generation-propagation. Consequently, the distance from the site to the epicenter is not a good parameter to characterize the seismic attenuation, or seismic intensity, which should correlate with other parameters; for instance, the distance to the "fault trace". This corresponds to the locus at the surface of the vertical projections of the most probable rupture initiation. In other words, the fault trace represents a sort of mobile epicenter. Accordingly, the distance to the classical epicenter is intentionally avoided in this paper.

Both mega earthquakes, with their tsunamis, were extremely destructive demanding the maximum resilience of the community to recover the sense of an organized life. From a geotechnical engineering perspective, both earthquakes have shown that one of the most important causes of catastrophic failures in any kind of structure is associated with the phenomenon of liquefaction. Remarkable evidence of this phenomenon is presented and discussed, along with the main factors that control it.

SHAKING DURATION AND LEVEL OF STRESSES

In the case of Maule earthquake, the peak accelerations recorded on rock outcrop and soil deposits are presented in Figs. 2 and 3, respectively. It is interesting to observe that PGA recorded on rock outcrop are surprisingly moderate, not exceeding 0.32g for any of the available recorded values. Nevertheless, in the coast line, immediately in front of the epicentral zone, there were no instruments to record the acceleration histories, and therefore, it is possible for this area to presume the occurrence of higher PGA than the ones reported. On the other hand, higher values of PGA were recorded on soil deposits, being the maximum 0.94g recorded in the city of Angol.

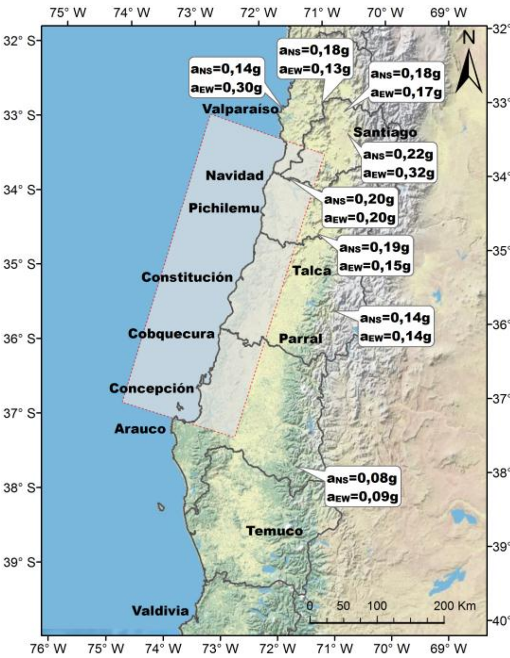

Fig. 2.- PGA recorded on rock outcrops Maule 2010 Chile Earthquake

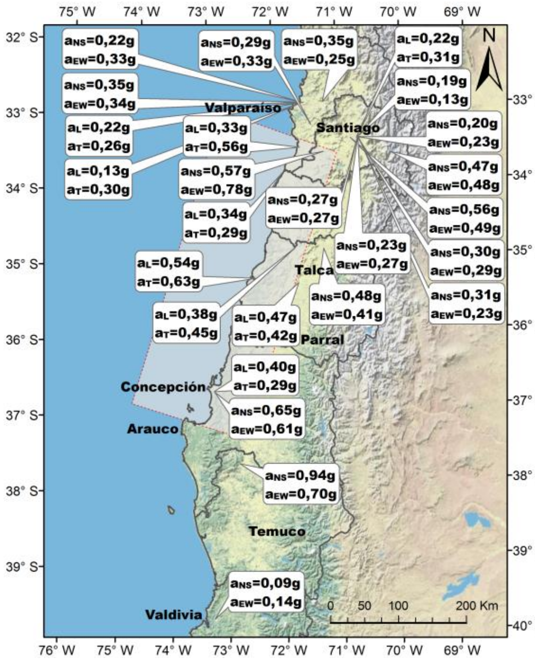

Fig. 3.- PGA recorded on soil deposits Maule 2010 Chile Earthquake

The acceleration time histories recorded on rock outcrop in Santa Lucia hill, located in Santiago (capital city of Chile), and their response spectra are presented in Fig. 4. It can be observed that the rock outcrop shaking shows a broad band of frequencies, in the range of 1 to 10 Hz (period of 1 to 0.1 sec). Additionally, the total duration of the quake is close to 2 minutes. The N-S component of three records obtained in different soil deposits are shown in Fig 5. It is important to mention that the total duration of the recorded motions is also more than 2 minutes, which is a long time of continuous vibration being applied to the existing saturated sandy soil deposits and it may explain the widely spread soil liquefaction observed during the Maule Earthquake.

Due to an enormous effort after the Kobe Earthquake, Japan has been able to implement a dense array of seismic stations for strong motions, which are well distributed throughout the country. Therefore, the 2011 Tohoku earthquake was well monitored. The data indicate that there are two sites where the PGA's were extremely high: 2.93g and 2.7g recorded at Tsukidate and Miyagi prefecture, respectively. In Tokyo, a PGA of 0.5g was recorded. According to the available information, the high acceleration observed at Tsukidate comes from a single pulse of high frequency, being the damage of the structures not significant. This confirms the empirical observation regarding the poor correlation between PGA with structural damage.

The N-S components of acceleration records obtained at Kashima, Sawara and Urayasu are shown in Fig. 6. These records were obtained in areas where liquefaction was clearly observed. From these records, it is possible to indicate that the seismic shaking continued for more than 2 minutes, with relatively large accelerations. In addition, between 20 to 40 minutes after the main shock, five large aftershocks struck the region. Therefore, for a quite significant interval of time, the existing saturated sandy soil deposits were subjected to seismic vibrations, which can be expected to be an important factor for inducing liquefaction.

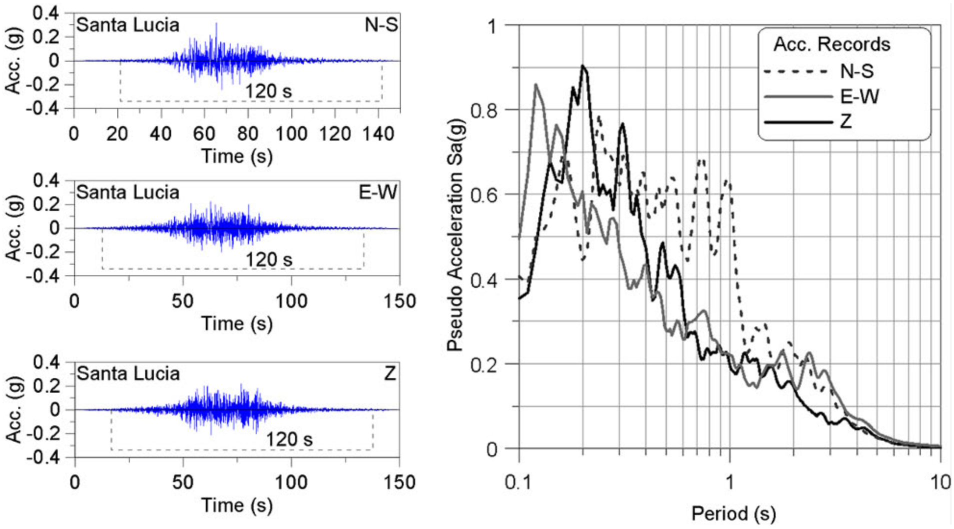

Fig. 4.- Acceleration histories and response spectra. Rock outcrop at Santa Lucia Hill, Santiago, Chile

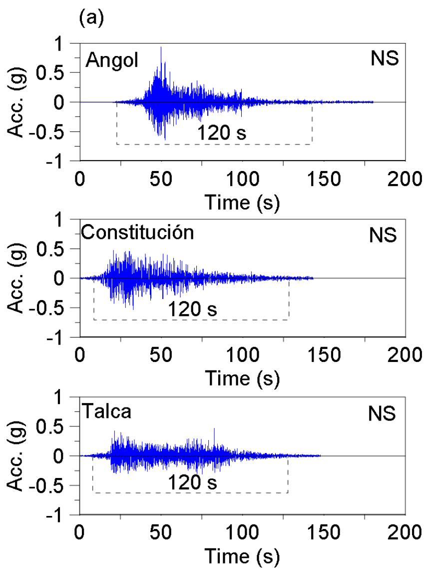

Fig. 5.- N-S acceleration records at three sites Maule 2010 Chile Earthquake (Renadic)

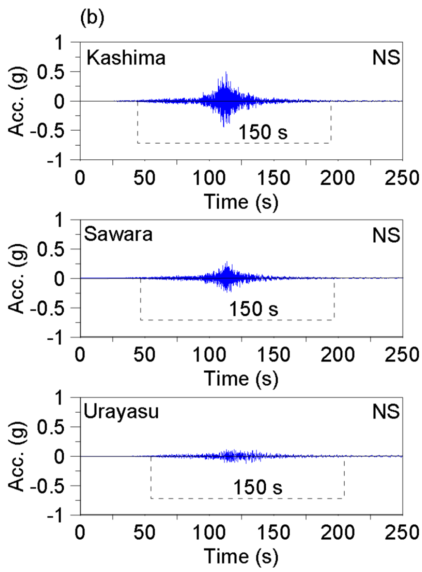

Fig. 6.- N-S acceleration records at three sites Kohoku 2011 Japan Earthquake (KiK-net)

The previous large earthquake that struck the Central part of Chile occurred on March 3, 1985. According to the geotechnical reports of that time, this earthquake, of Magnitude 7.8, did not induce liquefaction. The maximum horizontal accelerations were recorded in Melipilla city (approximately 60 km to the South-West of Santiago and 85 km to the South-East of Valparaiso). The N-S and E-W components were 0.67g and 0.60g, respectively. Therefore, the area around Melipilla has been subjected to similar level of shaking, in terms of acceleration, during both 1985 and 2010 earthquakes. It is important to understand that Melipilla city was significantly close to the epicenter area during 1985 earthquake (M= 7.8). On the contrary, for the 2010 earthquake (M=8.8) it was rather far. Both horizontal components recorded at Quintay and Zapallar during the 1985 Chile Earthquake are shown in Fig. 7. These sites are on the epicentral area. It can be observed that the total duration of these acceleration time histories is around 70 seconds, considerably shorter than the length of the records obtained from the 2010 Chile (120 sec) and 2011 Japan (150 sec) earthquakes.

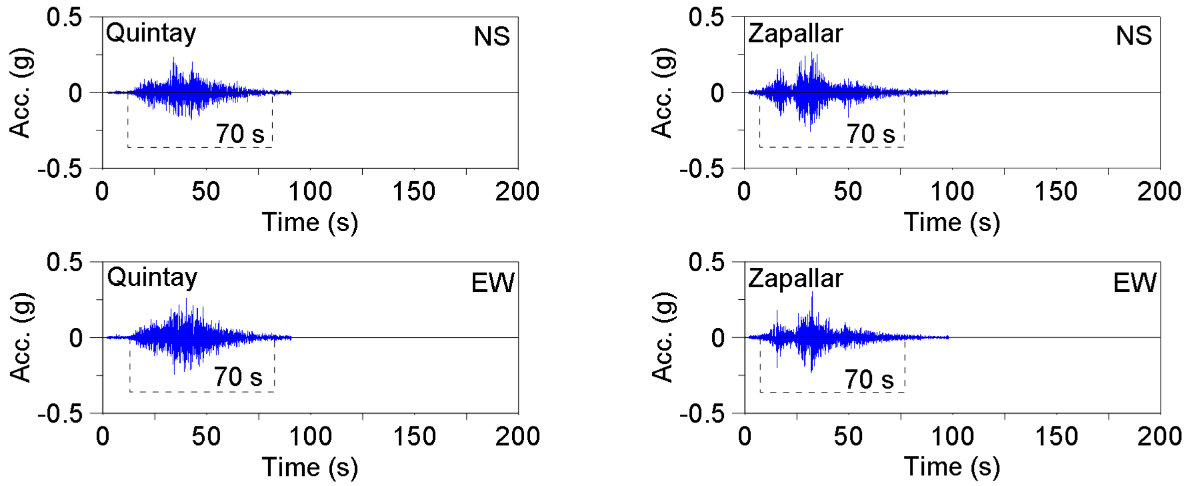

Fig. 7.- Acceleration records of Quintay and Zapallar, 1985 Chile Earthquake

Considering that almost no liquefaction was reported after the 1985 earthquake, it is postulated that the occurrence of liquefaction on the field is mainly controlled by the duration of the seismic load, followed by the level of cyclic stresses. This hypothesis will be supported with field observation presented below.

AREA AFFECTED BY LIQUEFACTION DURING 2010 CHILE EARTHQUAKE

Combining the damage reported in the extensive work performed by Astroza and collaborators (Ruiz and Astroza, 2012), with the infrastructure damage reported by the Ministry of Public Work, a map of intensity was elaborated, which is presented in Fig. 8. It is observed some irregularities in the isoseismals that reflect local site effects. The higher intensity (greater than VIII) are concentrated in three areas: the town of Navidad, the coastal area from Pichilemu to Constitution, entering the central valley in the towns of Santa Cruz and Talca, and the central depression in the towns of Cauquenes and Parral.

Regarding the occurrence of liquefaction, field observations have highlighted that the Maule 2010 Chile earthquake triggered liquefaction in more than 100 sites (Fig. 9). The northernmost site with evidence of liquefaction, corresponds to the limited slope instability experienced by the downstream slope of the tailings dam Veta del Agua, located approximately 13 km north-east of La Calera. While southernmost liquefaction occurred in Calafquén and Panguipulli lakes, located around 250 km to the south of the rupture zone. Consequently, the area with evidence of liquefaction covers a north-south distance of about 800 km, which corresponds to an area of almost twice the rupture zone.

It is observed that liquefaction sites cover an extensive area to the south of the rupture zone, which is much reduced to the north of the rupture zone. This fact could be explained by the limited existence of saturated sandy soils deposits to the north of Santiago, while saturated sandy soils are more common to the south of Concepcion, especially on the banks of rivers and lakes. The areas that showed more sites affected by liquefaction are in Concepción, Retiro – Parral and Paine (south of Santiago).

It is remarkable the fact that liquefied sites were observed in areas where the intensity was less than V. For example, the lateral spreading that involved banks of Lake Calafquén in the south (Fig. 10). The description of witnesses at Pucura sector (kilometer 10 of route Coñaripe - Lican Ray) states: "*We had a family of gypsies who were camping on the site when the shaking started, they shouted calling us, a once we got over there the water come out of the earth as a hose stream* "(website of the Panguipulli City Hall).This necessarily implies that the intensity of the quake, which correlates directly with structural damages, is not completely associated with the occurrence of liquefaction. Although this confirms the well-known dependence of the liquefaction strength on both level of cyclic stresses and number of cycles, it also shows the actual impact of the earthquake duration on the liquefaction strength.

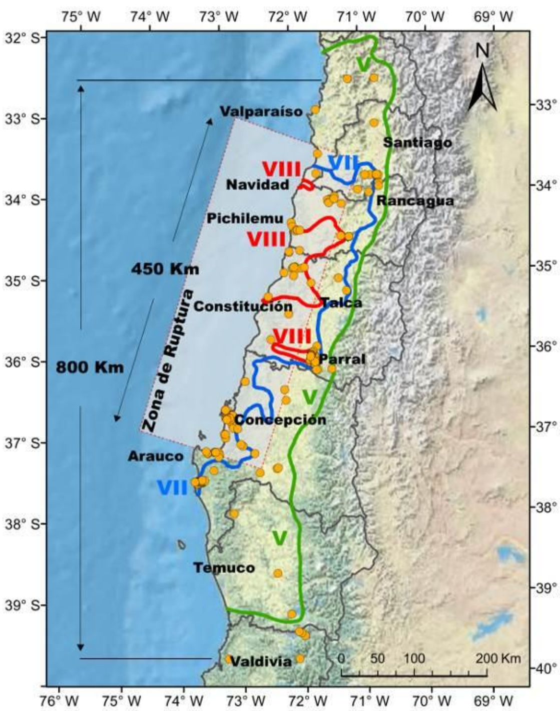

Fig. 8.- Intensity map, 2010 Chile Earthquake

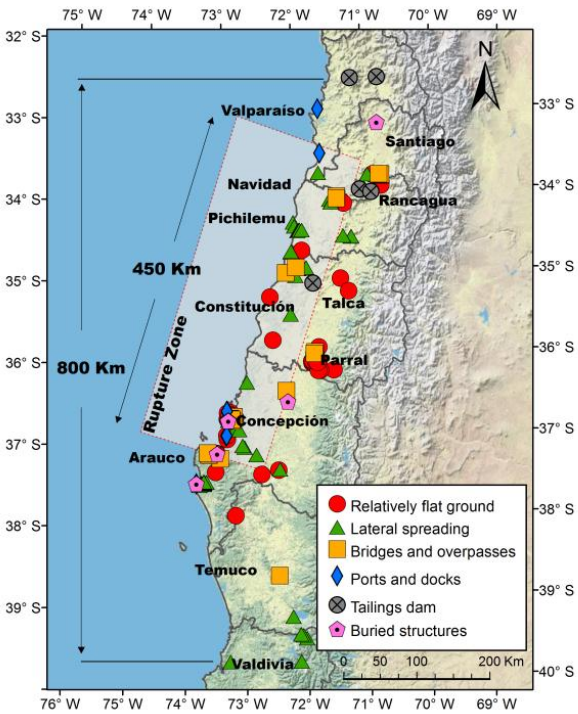

Fig. 9.- Sites where liquefied was observed during 2010 Chile Earthquake

Fig. 10.- Lateral Spreading observed in an area of low intensity: Pocura and Calafquen (source: Sernageomin and Municipalidad of Panguipulli)

LIQUEFACTION OF FLAT GROUND

The site inspection identified clear evidence of liquefaction in areas practically horizontal or with very gentle slopes. The most relevant cases took place in Concepción, Retiro - Parral, Arauco, Paine, Las Cabras and Nancagua. In Concepcion and surrounding areas, evidence of liquefaction was observed in the following sites: Sub Power Station Cementos Bio Bio, Brisas del Sol Condominium, The Presidents Condominium, Buena Vista Village, Villa CAP, Park Residential Collao and Bayonne. Additionally, liquefaction occurred also in Arauco City, in two wastewater lifting plants: Cochrane and Eduardo Frei.

One example is the case of Brisas del Sol Condominium, located in Talcahuano, where 5 houses located in front of a wetland (similar to a swamp) suffered lateral displacement up to 2 meters. One of the houses is shown in Fig. 11. Another case occurred near the City of Concepcion, where the railway collapsed in several places due to liquefaction and subsequent settlements, as shown Fig. 11.

Fig. 11.- Liquefaction of flat areas. Condominium Brisas del Sol and railway near Concepción (EFE)

LATERAL SPREADING

Lateral spreading is probably the most recurrent phenomenon observed after earthquakes on sloping ground, adjacent to river banks or lakes. Numerous cases of lateral spreading occurred along the rivers Nilahue, Mataquito, Itata, BioBio, Carampangue and Lebu. In some cases the cracks involved several kilometers along the river banks. Also, lakes were affected by lateral spreading: Laguna Aculeo, Rapel, Vichuquén, Calafquén, Panguipulli, and the main lagoons in Concepción. The sites where the phenomenon of lateral spreading occurred along the Lebu River are identified in Fig. 12.

Fig. 12.- Lateral spreading observed along the Lebu River. Maule 2010 Chile Earthquake

The large number of sites that were affected by lateral spreading corroborates that this is probably the most characteristic phenomenon associated with liquefaction failure.

From Fig. 13, it is possible to quantify the potential effect of lateral displacements and settlements. In this case, different sites along the northern bank of Bio Bio River collapsed deforming toward the river.

Fig. 13.- Cracks and settlements on right side of BioBio River caused by lateral spreading

LIQUEFACTION OF TAILINGS DAMS

The experience from observations in highly seismic regions shows that tailings dams are sensitive to earthquakes; in fact, several seismic failures have been reported throughout the years. However, most of these seismic failures have been described in tailings dams constructed under upstream method. It is worth to mention that properly designed tailings dams constructed using downstream or center-line methods have shown to be seismically stable. In Chile, where the seismicity is high and the mining industry is active, thousands of tailings dams are distributed throughout the territory, and several of them constructed by the upstream method have experienced failure due to liquefaction.

After the 2010 Chile earthquake five tailings dams constructed by the upstream method were reported with different levels of seismic failure: Chancón, Bellavista Dike No. 1, Veta del Agua Dike No. 5, Alhué and Las Palmas (Ramirez, 2010). Bellavista Dike No.1 collapsed, and a significant volume of tailings flowed into the Dike No. 2, which worked as a buffer, stopping the tailings flow. Dike No. 5 of Veta del Agua experienced a limited seismic failure; the toe of the dike moved down for a distance of 100 m, reaching El Sauce creek. Las Palmas experienced a catastrophic failure triggered by the 2010 Chile earthquake. The geometries before and after the failure are shown in Fig. 14 (Bray et al, 2011).

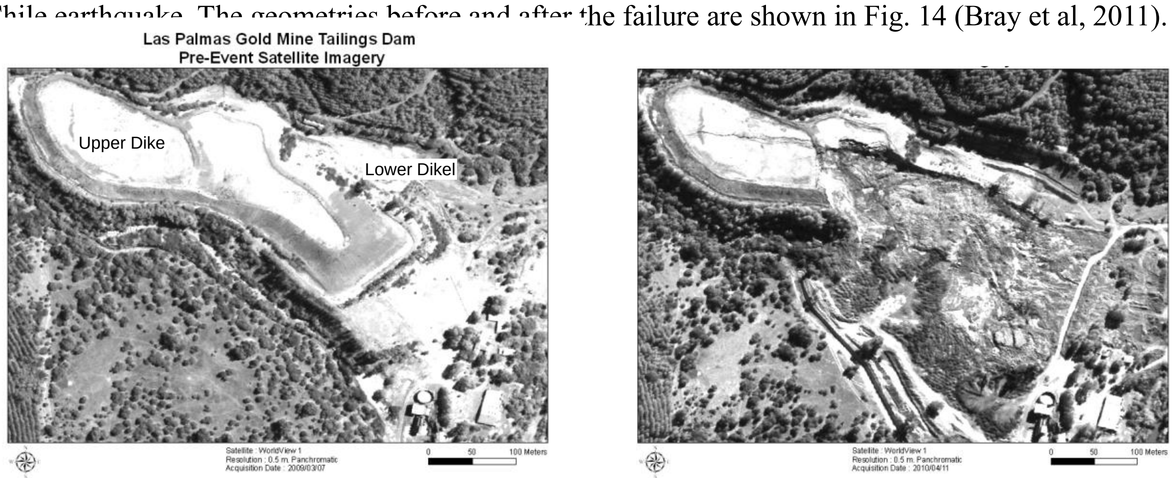

Fig. 14.- Pre-earthquake and post-earthquake satellite images of Las Palmas tailings dam

The tailings liquefied, flowing for a distance of about 0.5 km, killing four people who lived in a house that was buried under 4 m of tailings. The tailings dam consisted of two dikes (a lower one and an upper one), constructed in stages using the upstream construction method. This dam was operating until 1997, when the mining activity finished. From field observations it has been deduced that the bottom of this tailings dam was saturated, triggering a flow failure.

BRIDGES AND OVERPASSES AFFECTED BY LIQUEFACTION

According to all the information that has been collected and analyzed, 12 bridges and 4 overpasses were damaged by ground failure associated with liquefaction of ground foundations or accesses. Bridges affected by liquefaction of soil foundation were Andalién, Juan Pablo II, La Mochita, Niagara, Ramadillas, Raqui II, San Nicolas, Tubul and Yali I. Bridges with ground failure at the accesses were Alhue, El Durazno and Llacolén. Additionally, there were signs of liquefaction (settlements and sand boils) of the natural soil at Mataquito Bridge, which was not affected because the liquefiable soil was not used to support the structure. On the other hand, overpasses affected by the phenomenon of liquefaction were: Chada, Champa, Hospital and Los Pinos.

The location of these bridges and overpasses is shown in Fig. 15. It can be observed that there are two areas where there is a concentration of liquefaction phenomena. Failure of bridges is more concentrated in the Concepción area, whereas failure of overpasses is clearly observed to be concentrated to the south of Paine area, as shown in Fig. 16, where three additional sites liquefied.

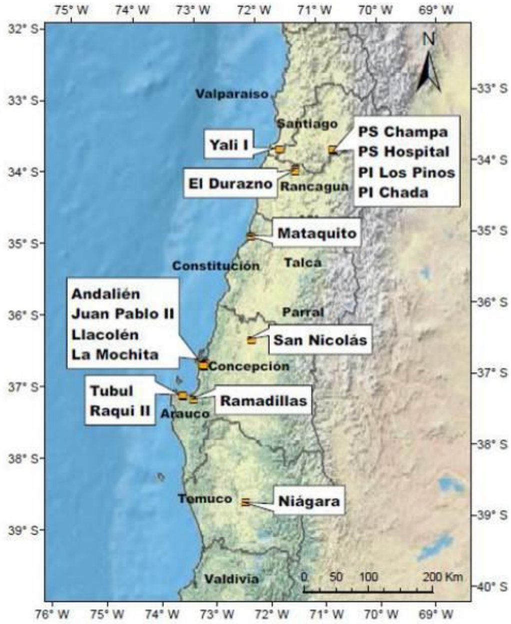

Fig. 15.- Bridges and overpasses affected by liquefaction

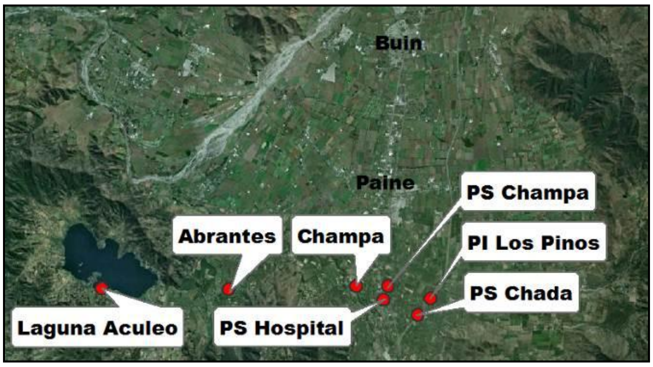

Fig. 16.- Concentration of liquefaction in Paine area

The bridge Juan Pablo II, located at the BioBio River, was the most seriously affected by the phenomenon of liquefaction. After the quake significant differential settlement showed up along the deck and the first pier (Concepcion abutment) collapsed due to the loads generated by lateral spreading (Fig. 17).

The topographic information obtained along both lines of the bridge allowed the assessment of the vertical deformation developed along the bridge. The result is presented in Fig. 18; around 15 piers developed settlements higher than 50 cm. In general, supports of the left longitudinal axis (upstream) developed greater settlements than those observed in the right longitudinal axis. Larger settlements are concentrated at the Concepción abutment bank. The largest settlement is approximately 1.8 m, followed by settlements of 1.1 m and 0.9 m.

Fig. 17.- Settlement caused by liquefaction, and failure due to lateral spreading.
Juan Pablo II Bridge affected by 2010 Chile Earthquake

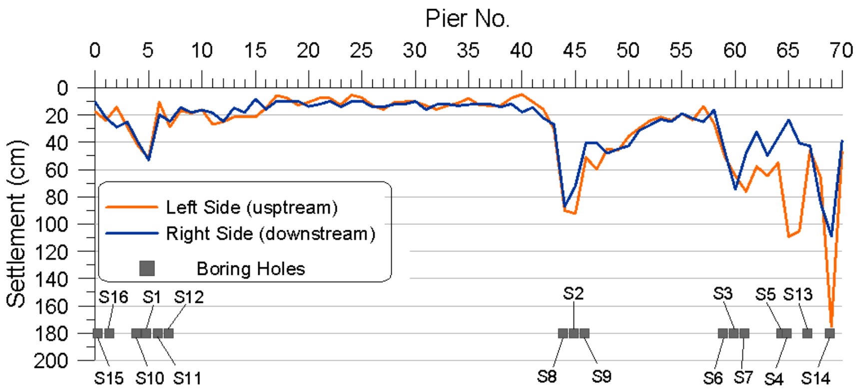

Fig. 18- Post-seismic settlements, Juan Pablo II Bridge

Because of the large differential settlements suffered by the piers, Juan Pablo Bridge was closed, and a series of 16 boreholes with N-SPT measurements was carried out by the Ministry of Public Works. Additionally, a limited number of classification tests were performed. The results are shown in Fig. 19, in terms of the normalized N_1-SPT (normalized to 1 kg/cm2) and the fines content.

The most interesting aspect of this case is associated with the fact that only vertical permanent displacements were developed. The absence of lateral displacements necessarily implies that there are layers of non-liquefiable soils that were able to develop sufficient lateral stiffness to stabilize the structure. The N_1-SPT confirms the existence of a highly stratified ground deposit, consisting of loose to dense sands and soft sandy silts. It is estimated that values of standard penetration tests $(N_1)_{60}$, exceeding 30 blows/foot are associated with layers of dense soil that should be responsible for the existence of enough lateral stiffness to prevent horizontal displacement.

It is important to indicate that, due to geological and tectonic issues, in Chile it is possible the occurrence of highly stratified soil deposits, where may coexist loose and dense sandy soils, with soft silts. As a consequence of this, the strength and deformability may be significantly different in both vertical and horizontal direction. This is the case of the ground that supports Juan Pablo II Bridge.

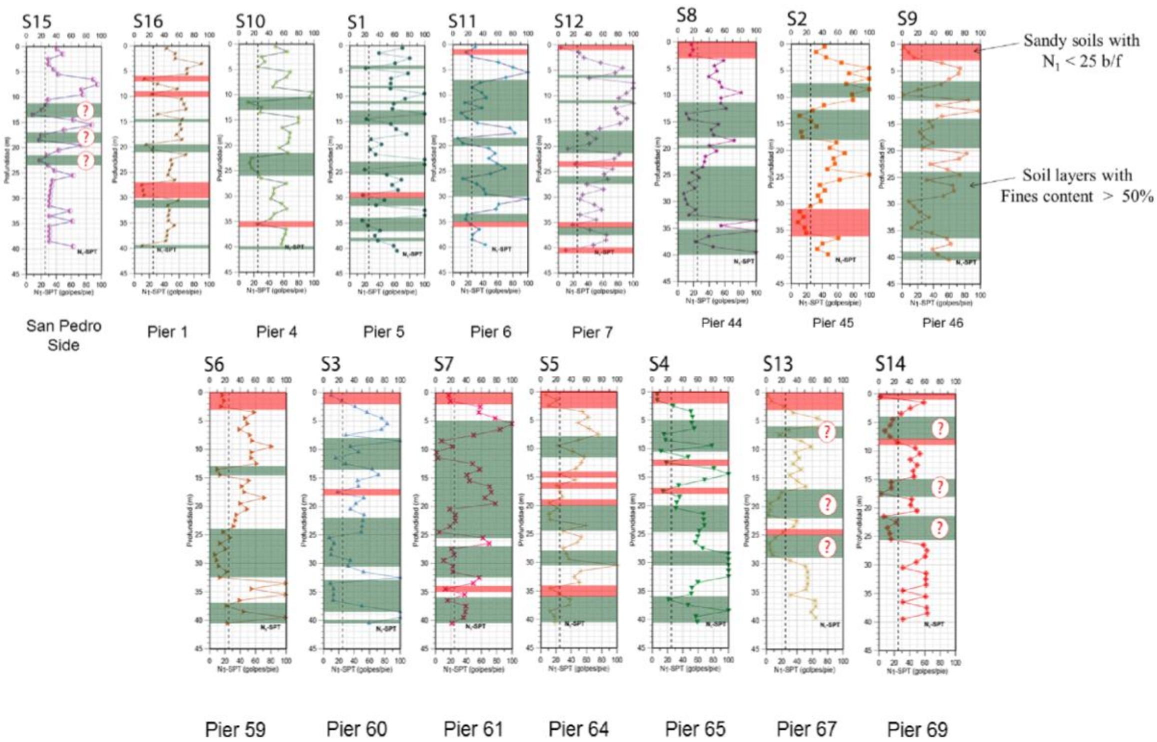

Fig. 19.- N_1-SPT, results obtained in Juan Pablo II Bridge

OBSERVED LIQUEFACTION IN PORTS AND DOCKS

Ports and quays were also affected by liquefaction of the coastline and the seabed. The most severe cases of failure occurred between Talcahuano and Lota, specifically in the La Poza (Talcahuano), Lo Rojas (Coronel), Lota Bajo (Lota) and the Port of Coronel areas. In addition, some industrial facilities located in Coronel also suffered the effects of liquefaction. Part of the damages observed in these coastal structures is shown in Fig. 20.

The liquefaction of the line shore soil, in addition to the inclination of the ground toward the sea, generated a lateral flow which dragged the piles. However, the end part of the docks was supported by non-liquefiable soils that prevented any horizontal displacement. Thus the piles kept the head in place, fixed by the supra-structure, but their bottoms moved toward the sea following the direction of the flow of the liquefied soil.


Fig. 20.- Damages observed in private infrastructure and Port of Coronel

LIQUEFACTION BY THE 2011 GREAT EAST JAPAN

The 2011 Tohoku Earthquake caused severe liquefaction in reclaimed lands. Tokyo Bay, including areas in Urayasu and Chiba City developed extensive liquefaction. Areas along the lower stream of Tonegawa River also liquefied, including sites in Katori of Chiba Prefecture and Itako City, Kamisu City and Kashima City of Ibaraki Prefecture (Tsukamoto et al, 2012; Tsukamoto et al, 2012).

Reclaimed lands that liquefied were constructed back in the 60´s, using soils dredged from the bottom of the bay. However, reclaimed lands that were improved by different techniques did not liquefy. Considering the vast extension of the reclaimed land, thousands of residential houses and buildings were affected by liquefaction, inducing settlement and tilt. Therefore, the most important liquefaction occurred in man-made fills.

CONCLUSIONS

The 2010 Chile Earthquake (M=8.8) induced liquefaction in more than 100 sites constituted by natural soil deposits and some man-made fills, covering an extensive area, being the largest distance in the north-south direction, of about 800 km. However, a previous earthquake that struck the central part of Chile in 1985 (M=7.8) did not trigger liquefaction. Although in both earthquakes, similar levels of accelerations were recorded in some areas, the 2010 Earthquake triggered liquefaction and the 1985 did not. Therefore, it is confirmed that the duration of the shaking is a key element that made the difference between those sites which presented liquefaction, from those that did not liquefy. This is a well-known fact, but it seems to be more important than it is supposed.

The liquefaction occurred due to the 2010 Chile Earthquake was mainly observed in natural ground, but, the widely spread soil liquefaction observed during the 2011 Japan Earthquake seems to be concentrated in man-made fill, associated with reclaimed land without improvement.

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