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Description and analysis of geotechnical aspects associated to the large 2010 Chile earthquake

Descripción y análisis de aspectos geotécnicos asociados al gran terremoto de Chile del 2010

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A description of the strong 27 February 2010 seismic event occurred in centre and south of Chile is presented. Main geology and geotechnical conditions of selected sites are described. The study focuses mainly, but not only, on the liquefaction phenomenon which affected housing developments in Concepción, Hualpén and San Pedro de la Paz. The earthquake occurred at the end of the summer, therefore ground dry conditions prevailed. However, grounds near to water bodies were still saturated, mainly in places which were previously part of swamps and wetlands. In some of these places the replacement of soft and loose soils for compacted sand fills was not enough to avoid the occurrence of liquefaction. It is suggested to consider other techniques of soil improvement or deeper foundations when the subsoil has low shear strength and hence potentially liquefiable. An example of dynamic compaction for a 1998 housing development project in Concepción, which performed successfully during this earthquake, is described. Failures in the Coihueco earth dam and in Las Palmas tailing dam are analysed. The former suffered cracks on the crest and a downward movement of a part of the upstream shoulder. The latter collapsed completely due to the widespread liquefaction leading to the flow of material downstream. Landslides of cliffs in the coast of Arauco and failures of bridges and embankments resting on soft soils are also analysed. Cliffs formed of marine sandstones and siltstones are believed to slide due to not only the strong seismic shaking but also due to large horizontal and vertical displacements experienced by the Arauco Peninsula. Finally, it is suggested to

Se presenta una descripción del evento sísmico del 27 de febrero 2010 ocurrido en el centro y sur de Chile. Se describen las principales condiciones geológicas y geotécnicas de los lugares seleccionados. El estudio se concentra principalmente, pero no solamente, en el fenómeno de licuación, el cual afectó conjuntos habitaciones en Concepción, Hualpén y San Pedro de la Paz. El terremoto sucedió al final del verano, por lo tanto predominaban condiciones de sequedad del terreno. Sin embargo, terrenos próximos a cuerpos de agua estaban todavía saturados, principalmente en sectores que eran previamente parte de pantanos y humedales. En algunos de estos lugares el reemplazo de suelos blandos y sueltos por rellenos de arena compactados no resultó ser suficiente para evitar la ocurrencia de licuación. Se sugiere considerar otras técnicas de mejoramiento de suelos o el uso de fundaciones profundas cuando el subsuelo tiene baja resistencia al corte y por lo tanto resulta potencialmente licuable. Se describe como ejemplo un proyecto de compactación dinámica de 1998 para un conjunto habitacional en Concepción, el cual no tuvo ningún daño durante este terremoto. Se analizan las fallas sufridas en la presa de tierra Coihueco y en la presa de relave Las Palmas. La primera presentó grietas en la corona y deslizamientos en una parte del espaldón aguas arriba. La segunda colapsó completamente debido a la propagación de la licuación, resultando en el flujo de material aguas abajo. También son analizados deslizamientos de acantilados en la costa de Arauco y fallas de puentes y terraplenes apoyados sobre suelos blandos. Los acantilados *carry out further research to study in more detail these preliminary findings.*

Keywords: liquefaction, soil improvement, wetlands, earth and tailing dams, landslides

compuestos de areniscas y limonitas marinas se considera que deslizan debido no sólo al fuerte movimiento sísmico sino también a los grandes desplazamientos horizontales y verticales experimentados por la península de Arauco. Finalmente, se sugiere realizar mayor investigación para estudiar en más detalle estos resultados preliminares.

Keywords: Nazca plate, subduction, rupture zone, seismic gap, uplift, subsidence

Seismological and geological background

On February 27th 2010, an earthquake of 8.8 in moment magnitude occurred with the hypocentre offshore the town of Cobquecura, around 100 km north of Concepción. The length of the seismogenic fault was estimated around 500 km along the Pacific Coast and 100 km wide. The part of Chile affected by the seismic and tsunami events ranges approximately from Valparaíso in the North (33º03'S; 71º46'W) to Temuco in the South (38º44'S; 72º35'W). The earthquake was triggered by the subduction mechanism, which consists in the sliding of the Nazca tectonic plate below the South America plate. The mechanism of subduction is very complex and is still under study by seismologists and geologists, since new features have been found such as the subduction propagation direction, initially towards the south and immediately afterwards towards the north (Barrientos 2010). Previously it was thought that earthquakes propagated only from the north to the south, like in the 1960 Valdivia earthquake. The subduction mechanism has been responsible for very strong earthquakes in the past. In fact, in May 2010 the 50 years anniversary of the worldwide largest seismic event registered in 1960 was remembered.

Spanish conquerors left written evidences of strong earthquakes and tsunamis from the XVI century. From those documents we know about enormous earthquakes with associated tsunamis in Penco (where Concepción was first founded on the coast) in 1570, 1657, 1730 and 1751. Due to this last earthquake in 1751 the people of Penco decided to move to a valley next to the Bío Bío river, where is nowadays located Concepción. In 1835 an earthquake destroyed the new founded city of Concepción and a tsunami devastated the close port city of Talcahuano. The earthquake of 1835 was described by Darwin (1845) as part of his journey in South America. The series of 1960's earthquakes was first felt in Concepción the 21rst May as a seismic event of magnitude 8.3 and the next day occurred the massive 9.5 moment magnitude seismic event, which propagated from Arauco to the south border of the Nazca plate with the Antarctic plate in the Gulf of Penas.

Figure 1 shows a general geological map of the affected area. Other cities within the affected area, for example Curicó and Talca are situated mainly in quaternary geology formations in the central valley or along the Pacific Coast such as San Antonio and Constitución. The coastal mountain range along the Pacific Ocean is covered by tertiary deposits, while the Andes Mountains, which is parallel to the coast, is made of tertiary and older rocks. The central valley between these two mountain ranges has deposits of quaternary formations. Quaternary soil deposits are also found in several lowlands along the Pacific Coast. However, those lowlands are mostly small except the one around Concepción. A cold sea current in the Pacific Ocean makes the climate in the affected region relatively dry during spring and summer (the earthquake occurred at the end of summer). In particular, the northern part receives much less precipitation than Concepción, for example. Typically, the average annual rainfall in Santiago is 350 mm/year, whereas in Concepción is around 900 mm/year.

The purpose of this article is to describe and analyse selected sites answering the question why damage occurred and why damage did not occur, mainly from the geotechnical point of view. With this in mind, damaged buildings, houses, bridges, road embankments, earth and tailing dams were inspected to find out what type of failure mechanisms might have controlled in case of poor geotechnical and structural performance.

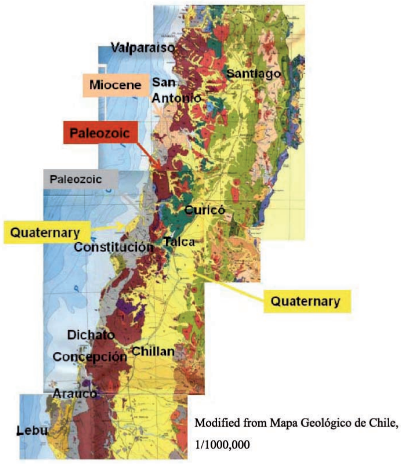

Figure 1: General geology in the affected area by the earthquake

One month after the earthquake (late March to early April), four Japanese Engineering Societies, namely Japan Association of Earthquake Engineering, Japanese Geotechnical Society, Japan Society of Civil Engineering, and Architectural Institute of Japan, jointly dispatched a reconnaissance team to investigate the damages in collaboration with specialists in Chile. This article was written as a partial product of this joint activity and focuses on geotechnical issues.

Liquefaction-induced damage in house developments

Soil liquefaction occurred in several places mainly because of the large earthquake magnitude. However, fortunately liquefaction was not so widespread since the ground water table was relatively low at the end of summer, except for sites close to water bodies or sites around or close to wetlands. The farthest epicentral distance of a liquefaction site was at Veta del Agua tailing dam, 350 km North. This distance is plotted against the surface magnitude 8.3 as a star in Figure 2, where it is possible to observe that the star is matches to the trend proposed by other authors (except Ambraseys 1988), based on experiences from past earthquakes.

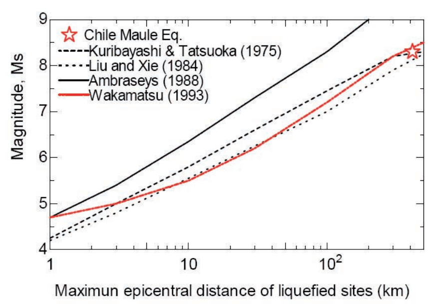

Figure 2: Relationship between seismic magnitude Ms and epicentral distance for the farthest liquefaction sites

The reconnaissance survey detected liquefaction at fill or replaced backfill in and around Concepción only, with the exception of Las Palmas tailing dam. In the Concepción area, subsoil liquefaction caused settlement of buildings and houses as well as uplift of underground tanks. The sites to be considered in this study are shown in Figure 3.

Figure 3: Sites considered in this study

Los Presidentes (1)

Figure 4a shows one of the four three-year-old apartment buildings of eight floors where liquefaction of the subsoil caused structural damage. It is possible to observe the tilted fence and booth at the entrance and material expelled by ejection from below the lawn and concrete block of the car park space. Evidence of sand boils was found around two buildings, which verifies the occurrence of liquefaction. Figure 4b shows the inclination suffered by the building Riesco, which is estimated around 0.77-degree. GEER7 (2010) estimated a maximum settlement of 40 cm on one corner and 10 cm on the other extreme. The report released by GEER (2010) also gives information about the damage in structural elements of the building. According to the soil mechanic study of the project a depth of ground water table of 1 m is considered for summer and a sand backfill of 4 m deep in replacement of the original loose sandy and silty soil deposits belonging to a wetland was recommended. The ground level is 15 masl, which is very low and explains the wetland condition of the area. The ground formation is recent and involves mostly fine sand transported by the Bío Bío River in times when the river formed a delta flowing to the sea. The building foundation consists of shallow strip footings 1.2 m wide and 1 m deep. The soil replacement was not deep enough to countermeasure the highly likely occurrence of liquefaction. Analysis of SPT data, of the original project, indicates that below the soil replacement, i.e. from 4 m to 11 m, estimated relative densities were less than 60% and safety factors against liquefaction were less than 1 for the Riesco building. The building in front of Riesco building suffered slightly less structural damage.

Since there is no SPT data available for this building, it is believed that favourable variations in soil deposits may explain this situation. The other two buildings next to the Riesco building did not suffer considerable structural damage and people are again living there. In this case a borehole data was available whereby relative densities were found higher than 60% between 4 m and 11 m and the safety factor against liquefaction was found higher than 1, except between 5.5 m and 7.5 m. This assessment is in agreement with the liquefaction evaluation following the procedure by Seed and Idriss (1971) based on the interpretation of SPT test and soil mechanics data (see also Kramer 1996).

Possible thoughts about the foundation design of the buildings may include the use of deep foundations. The election of a piled foundation does not avoid per se the occurrence of liquefaction and therefore requires also a careful design. Probably the use of basements together with deeper soil improvement techniques may be a good option. Gravel columns, cement or slime injection can be considered as possible ground improvement techniques to choose from. In any situation it is compulsory to carry out a more detailed soil exploration and geotechnical laboratory and desk studies, which includes deeper soil deposits, beyond 11 m.

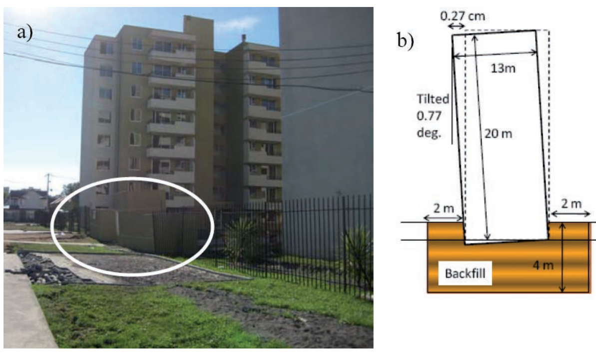

Figure 4: Building Los Presidentes a) granular material on the lawn and on a concrete block surface as a result of liquefaction and b) schematic cross section of the most tilted building

Brisa del Sol (2)

At Brisa del Sol a couple of less than one year old houses located along the border of a canal suffered serious lateral displacement and rotation. Figure 5a shows the enormous rotation of a house as a result of lateral movement of the foundation soil. Seismic forces caused the soil to displace around 2 m, as depicted in Figure 5b, which left houses without support, in other words soil foundation was removed. The ground is similar to that described for Los Presidentes buildings, i.e. loose and soft soil deposits as part of a wetland. On the other side of the canal the land is green due to shallow water table (Figure 5a). The ground improvement technique worked well for the majority of the housing development except for this border next to a canal. The 2 and 3 m of compacted sand used as a fill did not have more lateral restrain than a 2.5 m high narrow stone block wall which forms one of the canal side. In view of these evidences, it is not recommended to build a structure close to a border which does not have firm restrains to lateral movements. There are many types of retaining structures to hold an embankment such as concrete walls.

Figure 5: Houses at Brisa del Sol a) significantly tilted house and b) line of houses affected by ground lateral displacement

Valle Noble (3)

Valle Noble is a relatively new group of houses located on a flood area of the Andalién River. To avoid flood houses were built on top of approximately 3 m high fill soil, mostly sand although is also possible to find finer material. Only in a few houses strong ejection of fine material occurred in the garden and unfortunately in two houses ejection took place also inside the house. It is not know whether gaps between walls and floor slab already existed or elevated excess pore water pressure broke through. The river presence indicates that the water table is relatively superficial even during dry season. But the question is why this occurred only in a few houses. It is probable that the presence of a perched water table in this site together with the presence of a low permeability material, did not allow adequate dissipation of excess pore water pressure.

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Figure 6: Valle Noble a) location and b) large amount of fine material ejected inside a house

Bayona (4) and San Pedro del Valle (5)

San Pedro de la Paz is a town on the other side of the Bío Bío River. Around hundred thousand people live over there as a consequence of continuous constructions of housing developments. In San Pedro de la Paz soil deposits are mostly composed of loose to medium sand transported in the past by the Bío Bío River. However, there are also residual soils as a result of weathering of metamorphic rocks as part of hills and there are also organic and soft soils in low land areas belonging to wetlands. Figure 7a shows that Bayona, group of houses built in the early 90s, is located in the transition between residual soils on the lap of a hill and the former location of the wetland Los Batros. For the house construction, shallower soft and organic soils were replaced by compacted sand. However, this superficial improvement technique was not enough to avoid the occurrence of liquefaction in Ainoha Street shown in Figure 7b, where settlements in cm and direction of house rotation are shown. Figure 7c shows the case of a house with a subsidence of 17 cm. It is worth mentioning that settlements were not uniform and more pronounced under the house strip footing foundations, which resulted in the bulging of the house floor slab, breaking the slab and the covering of the floor. Pavement concrete blocks in the house entrances were also twisted and broken. Moreover, ejected fine soil was observed as a proof of liquefaction.

San Pedro del Valle (SPV) is a much more recent group of houses, around 2 years old, which shares practically the same characteristics of Bayona. Despite SPV is almost completely on Los Batros wetland, lesser houses suffered damage due to liquefaction or another soil phenomenon. However, the SPV sewage plant in Laguna Grande Avenue was found with important damage caused by what is called floating of buried structures. Sewage tanks were uplifted from their original positions in a very spectacular way as shown in Figure 8a. Two tanks of approximately 7 m deep rotated when uplifted around 1.2 m, breaking the steel pipe which connected them. Not well compacted sand used as a fill after excavating for the tank construction liquefied and caused the uplift of the buried tanks.

In addition, manhole uplifts up to 30 cm were observed in the middle and along of Laguna Grande Avenue. Figure 8b shows an example of an uplifted manhole. In general, this phenomenon is not taken into account in the design of sewage systems, hence further research in this topic is needed.

Figure 7: Bayona houses in San Pedro de la Paz: a) aerial view showing proximity to a lake and a wetland, b) measurements of settlements and c) house with a maximum subsidence of around 17 cm

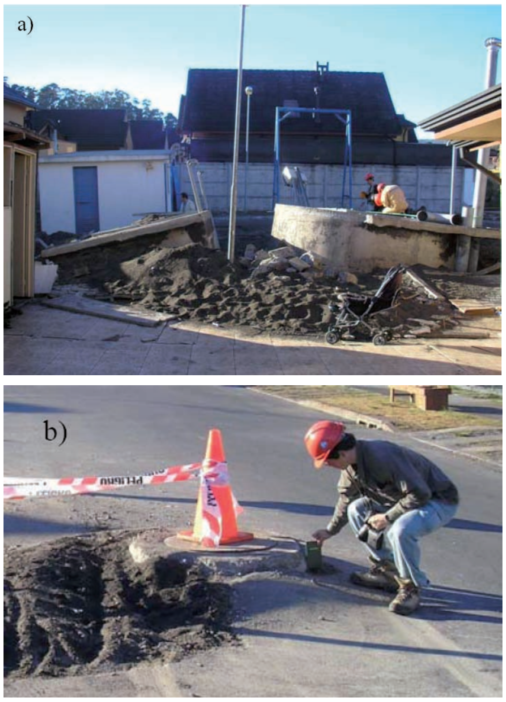

Figure 8: a) Uplift of buried sewage tanks in San Pedro del Valle and b) manhole uplifted

Ribera Norte Bío Bío (6)

It is important to highlight the well performance against the earthquake of a housing development project where dynamic compaction was used as a ground improvement technique. The project Ribera Norte Bío Bío was carried out in 1998 and 1999 with the purpose of reclaiming 10 hectares a flood swamp area close to the centre of Concepción and next to Bío Bío River North Bank. The project was initially studied by Poblete (1997), who proposed a grid with the sequence of impacts of a mass of 15 tons and 10 m of drop height. The project was subsequently performed by the consulting company Geotécnica Consultores, who based the soil improvement study on analyses of liquefaction potential of the replaced soil as well as the underlying soils (Verdugo, 1998). The sand replaced and used as a fill had 6 m thickness and the effect of densification is estimated to improve at least 10 m deep. To verify the dynamic compaction results a series of SPT tests were carried out before, during and after the dynamic compaction. The criterion was that that no liquefaction of the subsoil should occur even under strong earthquakes. It is worth pointing out that the promenade between the motorway and the Bío Bío River, where soil was not dynamically compacted, suffered considerable lateral spreading due to liquefaction, destroying pedestrian pavements, cycle paths, gardens, small shops, etc (see Figure 9b).

Figure 9: a) Housing developments in Concepción built on densified soil by dynamic compaction, no damage found and b) crossing the road, lateral spreading destroyed promenade

DAMAGES IN DAMS

Coihueco dam

Coihueco dam is situated 130 km to the East of Concepción and 30 km to the East of Chillán, capital of the province of Ñuble. The geology underlying the dam corresponds to what is called the Mountain formation, a mix of moraine, glacial and lacustrine sediments and due to the proximity of Cato River there are also fluvial terrace sediments. Coihueco is an earth dam made up of gravely soil with an impervious core protected on both shoulders with boulders. It has dimensions of 975 m in length, 31 m maximum height and shoulder slopes of 19 degrees upstream and 21 degrees downstream. The maximum reservoir area is 2.26 million m2. Since the earthquake occurred at the end of the dry season the reservoir water level was around 12 m lower than during winter. The dam suffered localised evidences of damage such as cracks and slides of dam material. Figure 10a shows two longitudinal cracks along the 5.2 m wide crest of the dam; one in the centre and the other one on the downstream shoulder side. The depth of the centre crack reached a maximum of 1.9 m, close to where the largest movement of the dam was found. This is shown in Figure 10b, where it can be observed the shoulder downward slip movement of the slope on the reservoir side, which extended for approximately 100 m. This movement resulted in a maximum subsidence of 3.3 m near the crest and an average horizontal displacement of 1.3m extending to the toe. In Figure 10b it can be also observed the presence of gravel on top followed by a wet fine material corresponding to the impervious core. A possible hypothesis is that the failure mechanism involves the sliding of the downstream shoulder made up of dry gravel over the impervious wet core material, which acted as a lubricated sliding surface. The question is why this occurred only in this section of the dam and did not propagate further. It is believed that humidity was kept because of the proximity of the dam buttress, where it can be seen in Figure 10a predominance of vegetation.

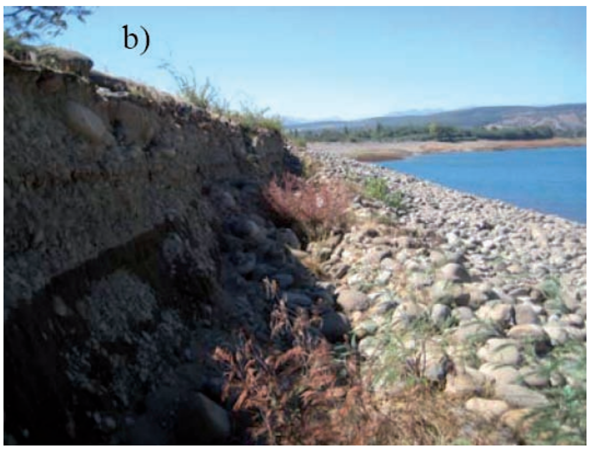

Figure 10: Coihueco dam a) longitudinal cracks at the dam crest and b) downwards movement of the upstream slope

Liquefaction in tailing dams

Chile is a mining country where the mining activity is concentrated mainly in the north of the country, hence not affected by the earthquake. However, some small and abandoned mines located in the south of Santiago suffered damage due to liquefaction of tailing dams. Tailing is a waste material produced by mining industries, which is the result from metallurgic processes to extract ore from the rock. In this form, valuable minerals are separated from powder of ores and the remaining stone powders are dumped into a water pond. Since the powders are as fine as silt, they sediment in water very slowly and form a loose and potentially liquefiable deposit. A further problem is that this saturated and fine grain size material has low permeability and, in case of seismic movements, high excess pore water pressure can develop. As a consequence, dissipation of high pore pressure can be substantially delayed. Therefore, the adverse condition of high excess pore water pressure plus low effective stresses can last for several minutes, even after the end of the seismic event. Moreover, this fine grain material has usually very low or practically no cohesion at all, thus increasing the likelihood of liquefaction further. The entire tailing dam deposit is supported by an embankment made of coarse components of tailings as well. There are two well known methods of tailing dam construction, namely down-stream and up-stream. The former is the safe one and should be used instead of the latter one. In case of up-stream construction, the embankment is nothing more than a surface coverage without structural strength. In case the underlying tailings liquefy, the coverage can not maintain stability anymore, resulting in a sudden tailing flow which can cause serious damage. The reader can find more information about liquefaction of Chilean tailing dams, for example, in Verdugo (2005).

Liquefaction of mine tailings occurred at Las Palmas near Curicó, Veta del Agua, and La Florida. The authors were able to inspect the significant damage at Las Palmas. Las Palmas is located in the coastal mountain chain of central Chile. This tailing reservoir was used as a deposit of a gold mine wastes between the years 1981 and 1997. Figure 11a shows an aerial view of the abandoned Las Palmas tailing dam where it can be observed that it is not really clear whether there was or not a dam or a wall to retain the tailings. It seems that ponds were extended forward as a plateau without being impounded. Figure 11b shows in dashed lines the area covered by the debris after the tailing flow failure (Figure 11c). Water and liquefied tailings erupted from many cracks at the surface as shown in Figure 11d. On the debris hundreds of little volcanoes could be seen, indicating that once the material flowed and rested in a new lower position, liquefaction occurred probably due to excess pore water pressure still accumulated or due to aftershocks. The liquefied mine tailings flowed down about 400 m and hit a farmer's house, killing four people who were buried to death under the tailing mass (Figure 11b).

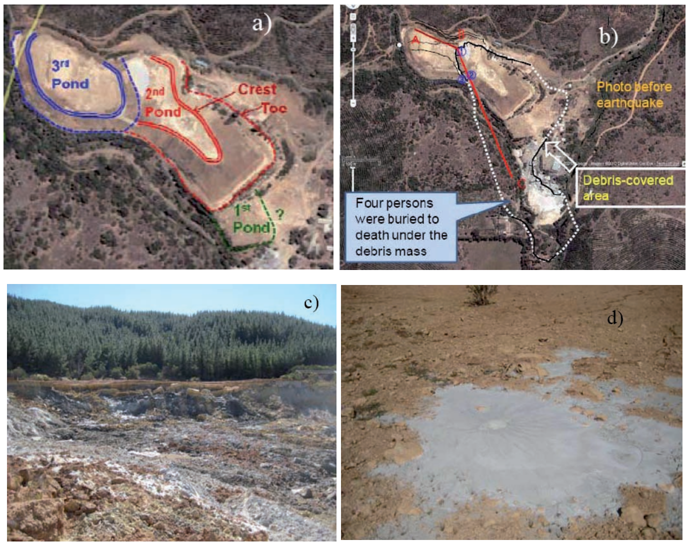

Figure 11: Las Palmas tailing dam: a) arrangement, b) geometry of the debris covered area, c) debris flow and d) isolated volcano on a pond

Landslides

During a heavy rain season it is not a surprise that dangerous landslides can occur in the Bío Bío Region. Notwithstanding the strong ground shaking induced by the earthquake, the dry condition of the ground seems to have reduced the number and extension of landslides. Although, several landslides were found in hills around Concepción, the volume of ground mobilised was not so significant because failures were relatively shallow. Different was the case of cliffs 100 m high in average found in the Arauco Peninsula, were large amount of ground slid. Figure 12 shows a geologic map of the Arauco Peninsula, highlighting the areas were landslides were observed. The material of these cliffs corresponds to different geological formations, but they are composed mainly of marine sandstones and siltstones. Figure 13a shows a landslide of the Navidad formation just at the entrance of the Raqui wetland (seen behind). The ground on the shore is made up of marine terrace sediments and in the wetland this material becomes a very soft organic peat. Figure 13b shows a landslide in the Tubul formation with a view behind of part of the Raqui wetland and the town of Tubul. In both landslides the failure surface is very steep with the material falling over the beach. It is important to know that, for this earthquake, the Arauco Peninsula is located approximately in the further South part of the Nazca plate section which dips under the South America plate. In other words, the further South aftershocks recorded were around this peninsula (Barrientos 2010). Moreover, large tectonic movements have been measured by GPS instruments and by visual observations. For example, in Concepción (50 km north from Arauco city) horizontal displacements between 3 and 4 m and uplifts in Punta Lavapié of around 2 m have been estimated (Barrientos 2010). It is believed that landslides were triggered not only by the strong cyclic motion but also by the lateral (towards the trench) and vertical (uplift) displacements of the earth crust. Further research is needed to understand the effect of coupling of this complex shaken plus pushing and uplifting on seismic slope stability.

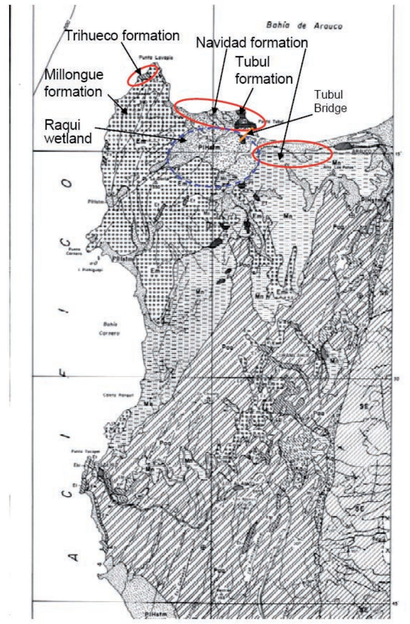

Figure 12: Geologic map of the Arauco Peninsula, showing in red ellipses landslide areas (Ferraris and Bonilla, 1980)

Figure 13: Landslides in coastal cliffs a) from the north and b) from the south of Tubul

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DAMAGE OF BRIDGES AND EMBANKMENTS RESTING ON SOFT GROUND

Figure 14 shows the complete collapse of Tubul Bridge. Tubul Bridge is the largest bridge of a series of three bridges located on the Raqui wetland. From the other two bridges of similar structural characteristics, Raqui I and Raqui II suffered complete failure of the embankment accesses, but only Raqui I did not have a deck collapse. These bridges had small and low reinforced concrete piers initially designed for a timber deck. Timber decks were later on replaced by high steel girders supporting reinforced concrete decks without making substantial changes to the piers. Since the bridges are founded on very soft and organic soils, it is believed that a significant seismic amplification took place during the earthquake inducing large displacements. The pier small area where the girders were resting was unable to cope with large and mainly horizontal displacements, although the collapse of the girders was probably eased by vertical displacements as well.

Possible solutions to avoid this type of collapse need to be carefully studied owing to the very poor quality of the foundation soil in conjunction with strong seismic events. Soil improvement techniques for the embankments have to be considered reaching a deep enough depth into the organic soil. There are methods such as gravel or sand compacted columns, chemical or cement injections can also be considered as well as solutions using geosynthethic materials. Piers should be enlarged to allow girders to move without falling from the pier.

Figure 14: Tubul Bridge a) aerial view showing complete deck collapse and b) failure of bridge access

Figure 15 shows the collapse of the road embankment which is the access to the town of Lota. This 16 m high embankment had originally only one road with two carriageways. In the beginning of the 90s a second road with two carriageways was added next to the original one. Both road embankments were founded on a soft soil, saturated the whole year. For that reason the embankment slid over both side of the road destroying completely the asphalt road and everything around. Even assuming a good quality of compaction of the embankment fill, this did not avoid a highly likely amplification of the seismic waves. Since the soil where the embankments were founded corresponds to a saturated, soft and low permeability soil, non dissipated excess pore pressure generated during the earthquake reduced the undrained shear resistance of this soil. This resulted in the development of failure surfaces over where parts of the embankments slid. It is also believed that the contact surface between the old and newer embankment may have acted as a sliding surface too.

Figure 15: Road embankment collapse at the entrance of the town of Lota2

Concluding remarks

This article presents a study of damages related to geotechnical aspects encountered by the authors during a reconnaissance inspection immediately after the earthquake. From observations and geological and geotechnical information, preliminary conclusions can be drawn. It was fortunate that the earthquake occurred during the end of the dry season. This found water tables much lower and therefore soil deposits were not saturated up to relatively deeper depths. Notwithstanding the dry season, in areas close to water bodies and especially close to wetlands, shallow soil deposits were still saturated. Saturated soil deposits and strong seismic loading added to poor drainage conditions and low bearing capacity of cohesive or non cohesive soils led to ground failures. The use of compacted embankment fills did not always prevent failure, particularly when underlying soils reduced substantially their undrained shear strength.

It is emphasized here that the understanding of failure mechanisms during earthquakes is a key issue for developing the necessary provisions to avoid or at least mitigate damages in future earthquakes.

It was considered important to present an example where no damage was found due to the well use of an appropriate soil improvement technique. The use of dynamic compaction showed no damage at all to a 10 hectares of the north Bío Bío bank housing project. In view of this example of well geotechnical performance and the examples of negative geotechnical performance presented in this paper, it is clear that the use of soil improvement techniques or deeper foundation solutions should be the direction to follow onwards when difficult grounds are not appropriate to found structures directly.

There are several topics for further research. Analyses of acceleration recordings available around Concepción are necessary. Unfortunately, the authors are not aware of recordings in rock outcropping and soil in the same site to obtain soil transference functions. Evidences of topographical amplification close to hills or rivers have not yet been found either. The extension of seismic microzonification studies is required. Manhole design to avoid uplifting, failure of piers in Coronel and Lota and scour of foundations due to tsunami are also further topics of research.

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