Case History

Geotechnical damage caused by the 2010 Maule, Chile earthquake

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1. INTRODUCTION

The country of Chile is located along the subduction of Nazca tectonic plate, that is moving at the rate of 7 cm/year , against South America. Consequently, many gigantic earthquakes have affected this country in the past. For example, the event in 1960 registered 9.5 in magnitude and caused significant damage in its south part including Valdivia. Another event in 1985 was of magnitude of 7.8 and affected the central part of the country where Valparaíso and San Antonio are situated (Troncoso, 1989).

On February 27th, 2010, the Maule earthquake of 8.8 in moment magnitude occurred in a region between those two former earthquakes. The epicenter was located near Cobquecura. The length of the seismogenic fault was estimated to be around 450 to 500 km along the Pacific Coast. This means that Santiago, the capital, and Valparaíso are located near the north boundary of the fault, while Concepcíon near the south end. Cities in the affected area are situated either in the central valley (Quaternary geology in Fig. 1) or along the Pacific Coast. Buildings, houses, bridges, road embankments, tailing dams and other structures were damaged by the earthquake.

Figure 1 illustrates the geological condition in the affected area. The coastal mountain range along the Pacific Ocean are covered by Tertiary deposits, while Andes Mountains, which is parallel to the coast, is made of Tertiary and older rocks. The central valley between these two mountain ranges has a deposit of Quaternary soil. Quaternary soil deposit is also found in several lowlands along the Pacific Coast. However, those lowlands are very small except the one around Concepción.

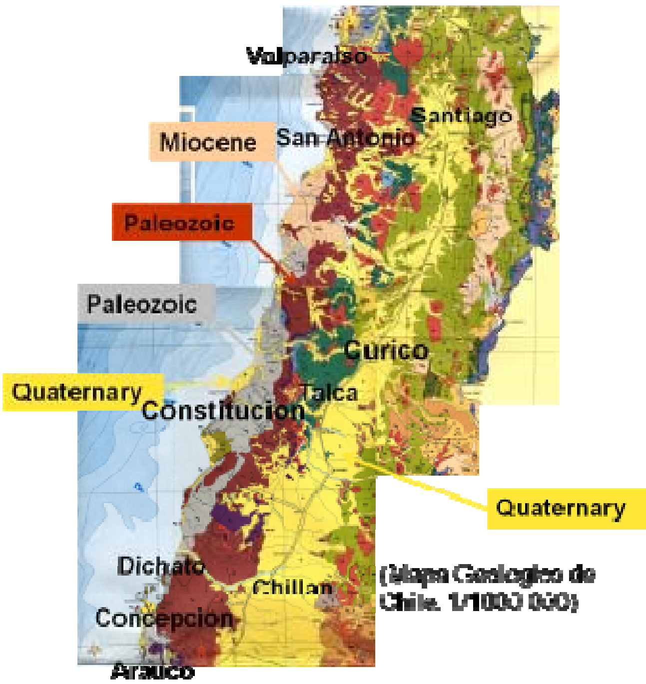

Fig. 1 Geological map in the affected area by the earthquake

A cold sea current in the Pacific Ocean makes the climate in the affected region relatively dry. In particular, the northern part receives less precipitation than the southern part. Typically, the average annual rainfall in Santiago is only 350 mm/year.

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About one month after the earthquake (late March to early April), four engineering societies in Japan, which were 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.

2. LIQUEFACTION-INDUCED DAMAGE

Soil liquefaction occurred at a variety of places because the magnitude of the earthquake was large. The greatest epicentral distance of liquefaction site is 300 km at Veta del Agua tailing dam in the northern part. This farthest distance is plotted against the magnitude in Fig. 2 to show good compatibility with experiences during past earthquakes.

The actual number of liquefied sites was quite small in spite of the large earthquake magnitude. This is probably because the low level of annual precipitation does not make many water-saturated sandy subsoil. The reconnaissance survey detected liquefaction at fill or replaced backfill in and around Concepción only, except the tailing dam at Las Palmas. In Concepción area, subsoil liquefaction caused settlement of buildings and houses as well as uplift of underground tanks at sites shown in Fig. 3. Photo 1 demonstrates a 0.77-degree tilting of an 8-storied apartment building at Los Presidentes in Hualpén. Sand boils were found around the building to verify the occurrence of liquefaction. As the original topography here was swamp, subsurface soil was excavated down to the depth of 4 m and then sand was placed at the time of construction (see Fig. 4). Ground water table was as shallow as 1.0 m below the surface, and it made the effects of subsoil liquefaction more influential. Similar settlement occurred to a 5-storied hospital building in Curanilahue at about 30 km south of Concepción.

Many houses settled in three housing lots in Concepción as shown in Photo 2. The maximum settlement was about 17 cm. Because the original topography here was swamp as well, the backfilled sand in the swamp liquefied and caused house to subside. Furthermore, underground tanks uplifted in cities of Concepción, Chillan, and Arauco. Photo 3 shows uplifted sewage tanks. It seems that backfilled sand liquefied and caused this uplift.

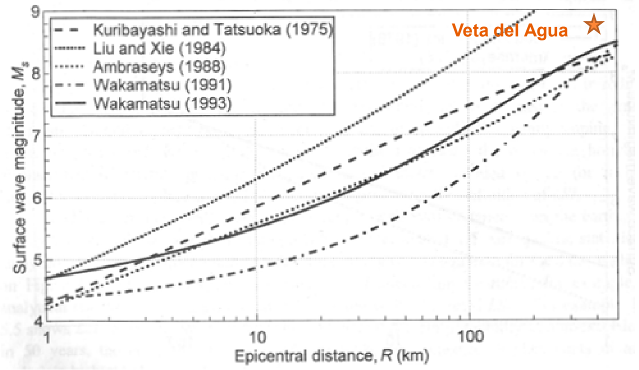

Fig. 2 Relationship between seismic magnitude and epicentral distance at farthest liquefaction sites

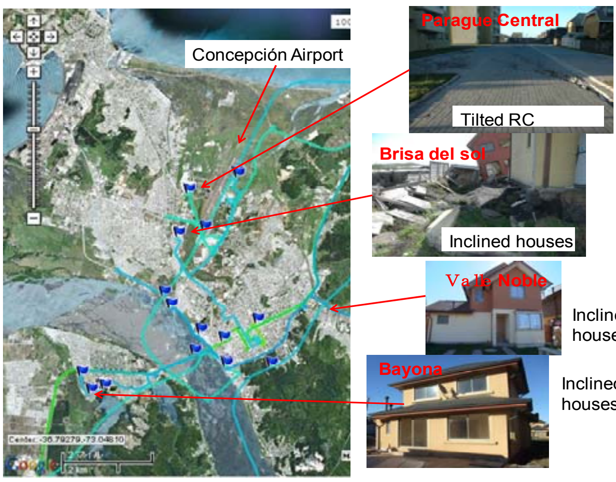

Fig. 3 Sites of liquefaction damage in Concepción

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Photo 1 Tilting of apartment building at Los Presidentes

Photo 2 17-cm Subsidence of houses in Bayona, San Pedro de la Paz

Photo 3 Uplift of buried sewage tank in San Pedro de la Valle

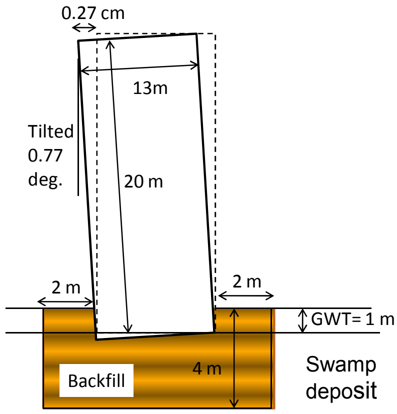

Fig. 4 Schematic cross section of tilted building

(Densification by dynamic compaction)

Photo 4 Apartment buildings without damage in Concepción

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On the contrary apartment buildings in Photo 4 survived the quake although liquefaction occurred in its neighborhood. This is because the foundation soil of these buildings had been densified by dynamic compaction method and liquefaction resistance had been increased. This is an important evidence to validate the effects of this soil-improvement technology.

3. DAMAGE IN DAM

3.1 Liquefaction in Tailing Dam

Tailing is a waste material that is produced by mining industries. Valuable minerals are removed from powder of ores and the remaining stone powders are dumped into a water pond (Photo 5). Since the powders are as fine as silt, they sediment in water very slowly and form a loose and liquefiable deposit. Further problem is that this fine grain size reduces the permeability (hydraulic conductivity) of this material and, in case of liquefaction and high excess pore water pressure, the dissipation of high pore pressure is substantially delayed. Therefore, the adverse condition of high pore water pressure and low effective stress lasts for a long time. Moreover, this fine grain has no cohesion, thus increasing the liquefaction probability further. The entire tailing deposit is supported by an embankment made of coarse components of tailing as well. In case of up-stream construction, this embankment is nothing more than a surface coverage, and if the underlying tailings get liquefied, the coverage cannot maintain stability anymore. Hence, a tailing flow occurs.

Fig. 5 Location of liquefaction of mine tailing.

Liquefaction of mine tailings occurred at Las Palmas near Curico, Veta del Agua, and La Florida (Fig. 5). Among them, the authors were able to visit the significant damage at Las Palmas. This tailing dam was used for wastes from a gold mine between 1981 and 1997. An abandoned tailing dam collapsed as shown in Photo 6. Photo 7 illustrates details of the collapsed dam. Accordingly, water and liquefied tailings erupted from many cracks at the surface (see Photo 8). The liquefied mine tailings flowed down about 400 m and hit a farmer's house (Photo 6). Consequently, four people were buried to death under the tailing mass.

Photo 5 Reservoir of tailing dam at Veta del Agua in 1993.

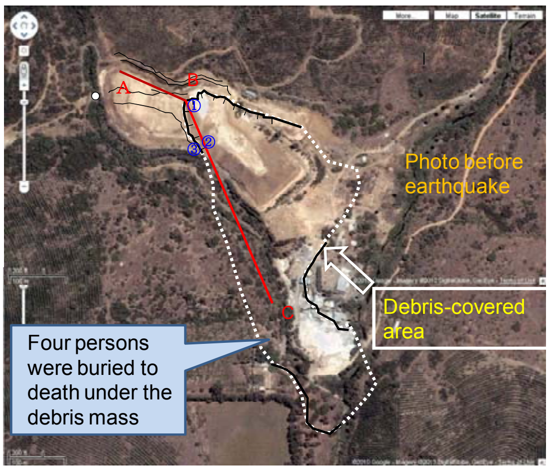

Photo 6 Extent of damage at Las Palmas tailing dam.

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Photo 7 Tailing deposit after liquefaction

Photo 8 Eruption of liquefied tailings at Las Palmas

3.2 Damage of Water Dam

Coihueco Dam is situated at around 130 km to the east of Concepción. It is an earth dam and measures 975 m in length, 31 m in the maximum height, 19 degrees in the upstream slope, and 21 degrees in the downstream slope. The reservoir area is 2.26 million m2. Photo 9 indicates two longitudinal cracks along the crest of the dam; one in the centre and the other at the downstream (right side) shoulder. The width of the crest is 5.2 m. The depth of the crack reached at maximum 1.9 m. Photo 10 demonstrates the downward slip movement of the slope on the reservoir side. This movement resulted in at maximum 3.3 m subsidence near the shoulder.

Photo 9 Longitudinal cracks at the crest of Coihueco Dam

Photo 10 Downward slope movement in upstream face

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4. FAILURES OF SLOPES AND EMBANKMENTS

It was fortunate that the size of failures in natural slopes was small. This is because the Andes Mountains where there are many unstable slopes were far from the earthquake-affected area. The Coastal Mountains conversely do not have many steep slopes except cliffs at the coast. Therefore, the present report on natural terrain addresses only the coastal region. There are many steep cliffs along the coast from Arauco to Lebu through Cape Lavapie and they are subject to shallow failures. Photo 11 and Photo 12 indicate surface failures near Arauco and Cape Lavapie, respectively. Height of the cliff shown in Photo 11 is about 100 m.

Photo 11 Slope failure at Las Peñas near Arauco

Photo 12 Slope failure at Lavapié

Photo 13 Minor slope failure at San Antonio

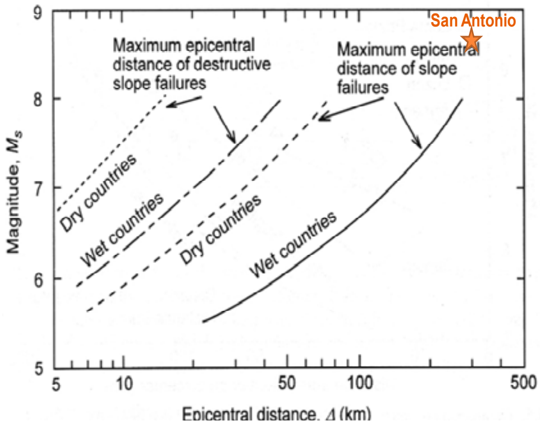

Fig. 6 Relationship between magnitude and epicentral distance to farthest landslide sites (TC4 of ISSMGE, 1999)

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Photo 14 Peaty ground in and around Tubul

Photo 15 Collapsed bridge in Tubul

Photo 16 Collapsed approach embankment of Raqui II bridge

Photo 17 Big slide of road embankment in Lota Norte

Although being very minor, a slope failure with the longest epicentral distance occurred in San Antonio (Photo 13). Its epicentral distance of about 300 km is plotted against the seismic magnitude in Fig. 6 to support the relationship between magnitude and maximum distance of slope failure that was proposed in the Seismic Zoning Manual by TC4 (TC4, 1999). The plotted point is between two curves for dry countries and wet counties. Because the slope failure in Photo 13 is very minor, it may be reasonable to shift the point to the left.. Anyway, although the magnitude of the earthquake was huge, the size of slope-failure area was small as compared with that in wet counties.

5. DAMAGE OF BRIDGE AND EMBANKMENT RESTING ON SOFT GROUND

The subsoil condition between Arouco and Tubul consists of very soft and peaty soil (Photo 14). Consequently, three bridge girders fell down (Photo 15) and approach embankments collapsed as shown in Photos 16 and 17. The mechanism of the collapse of girders needs further investigation, but the effects of soil condition deserve careful study.

In Chile, road embankment is generally constructed only at approaches to bridges. Thus, damaged embankment was found at a limited number of places. Photo 17 shows the biggest failure of road embankment that occurred in Lota. This embankment was constructed upon a swampy soil with a height of 16 m. Its construction material was clean sand. It seems therefore that pore water pressure increased at the bottom of the embankment during shaking, leading to loss of shear strength and shear failure.

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6. DAMAGE IN HARBOR STRUCTURES

Coronel Harbor is located at about 450km to the south of Valparaiso. A distortion occurred in a fishermen's pier there (Photo 18). The damaged structure connects the land and the main part of the harbor and is supported by a pile foundation. Because substantial translation and tension cracks were found on the land side of the pier (Photo 19), it is inferred that the structure was subjected to compression from the land side, and, because of the very rigid foundation of the main part of the offshore pier, the connecting part developed significant compressional deformation and buckling. This soil-structure interaction deserves further study. Note that two larger commercial piers next to this place received only minor effect from the earthquake and were able to start operation one day after the earthquake.

Photo 18 Damaged pier in Coronel

Photo 19 Lateral flow of soil adjacent to the pier

7. REMARKS ON TSUNAMI EFFECTS

Tsunami disaster was reported widely after the earthquake. The height of the wave was 5.6 to 28.3 m in Constitución, 5.3 to 7.3 m in Dichato, 2.8 to 6.4 m in Talcahuno, and 5.2 m in San Antonio. High waves claimed significant human loss and destroyed many structures. One of the reasons for different tsunami heights at different places is the local topography. This section addresses the Coliumo Bay and Dichato area for example (Fig. 7). Photo 20 shows the total devastation near Cape Blanca. This damage occurred on the southeastern side of the cape facing the Coliumo Bay. This is in a clear contrast with the Pacific Ocean side of the cape where no significant damage occurred. It deserves attention that a sea wall in this damaged area functioned satisfactorily (Photo 21).

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Fig. 7 Map of Dichato and Coliumo Bay area

Photo 20 Tsunami damage near Cape Blanca

Photo 21 Successful performance of sea wall in Cape Blanca area.

Photo 22 Tsunami erosion in coastal area of Dichato

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Photo 23 Tsunami-induced erosion in Dichato

Photo 24 Exposure of buried lifeline after tsunami erosion

Photo 25 House that floated when tsunami came

Photo 26 House that did not float when tsunami came

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Photo 27 Tsunami protection by embankment (drawn on Google Map)

Photo 22 indicates a long-distance view of Dichato. Although it is not visible in this photograph, the coast of this town was eroded by the tsunami as shown in Photo 23. It is noteworthy that even an underground facility was affected by tsunami-induced erosion of soil; see Photo 24. Photos 25 and 26 demonstrate effects of foundation on damage extent of houses. The house in Photo 25 floated when the water level rose and was transported over a long distance. In contrast, the house in Photo 26 was tightly connected to the foundation and was able to stay in the same place. The intact shape of this house may suggest that the impact force of the tsunami was not very strong. Finally, Photo 27 presents an interesting case where a 6-m-high road embankment protected a freight container yard from the tsunami attack.

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8. REMARK ON BUILDING DAMAGE

Several buildings collapsed in Santiago, Curico and Concepción. Some of them had weak pillars as shown in Photo 28. When substantial inertia force occurred in the massive superstructure, the ground floor, that consisted only of pillars without a reinforced wall, was easily destroyed. This type of structural failure has been experienced in many past earthquakes.

Photo 28 Collapsed building at Maipú in Santiago

9. CONCLUDING REMARKS

The authors conducted a damage reconnaissance study in Chile after the gigantic Maule earthquake in 2010. Although the magnitude of the earthquake was as large as 8.8, damage to structures was limited except tsunami-induced ones. In particular it was fortunate that liquefaction and landslide occurred at few sites only. On the other hand the importance of soil-structure interaction in damage generation was found in harbour structures and underground lifelines. This issue needs further consideration.

10. ACKNOWLEDGEMENTS

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11. REFERENCES

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