TECHNICAL ARTICLE

OVERVIEW OF GEOTECHNICAL DAMAGE CAUSED BY THE 2010 CHILE EARTHQUAKE

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1.- THE 2010 CHILE EARTHQUAKE

On February 27, 2010, at 3:34 a.m. local time, a large earthquake of Magnitude 8.8 hit the Central-South region of Chile. A significant number of aftershocks followed the initial quake, among which the most important one of Magnitude 6.2 occurred 20 minutes after the main shock. The earthquake triggered a tsunami that struck off the Chilean coast, devastating many towns located onshore, causing additional deaths and widespread damages.

The 2010 Chile earthquake is associated with the subductive seismic environment generated by the collision between the Nazca and South American tectonic plates, which are converging at an estimated rate of 65 to 80 mm per year. The Nazca plate is subducting below the South American plate, moving down and landward. The 2010 Chile Earthquake has been identified as a thrust-faulting type that occurred on the interface between both two plates, at an average depth of 30 km. The involved rupture zone covered a rectangular area of approximately 450 km by 170 km (see rectangle in Fig. 1). The earthquake together with the tsunami caused nearly 600 casualties and an estimated economic loss of 30 billion US dollars.

Horizontal peak ground accelerations (PGA) recorded on rock outcrop and soil deposits are presented in Fig. 1. It is interesting to observe that horizontal PGA recorded on rock outcrop are surprisingly moderate; none of the available data being greater than 0.32g. Nevertheless, it is important to mention that in the coast line, immediately in front of the epicentral zone, no instruments were available. Therefore, for this area it would be possible to presume the occurrence of higher PGA values than the ones reported. On the other hand, as expected, higher values of horizontal PGA were recorded on soil deposits, the maximum one being 0.94g, which was recorded in the city of Angol, located to the south of the rupture zone. To the north of the rupture zone, the maximum horizontal PGA was recorded in the City of Melipilla, reaching a value of 0.78g.

It is important to mention that several of the available records show a ground motion that exceeds 2 minutes of duration. Two examples can be observed in the acceleration time histories recorded in the cities of Talca and Constitucion (Fig. 2). The long duration of the ground motions seems to be characteristic of earthquakes of large magnitude that definitely increases their potential destructiveness.

On the other hand, according to the reported rupture zone (a rectangular area of approximately 450 km by 170 km), the usual concept of epicenter associated with a single point does not adequately represent the actual phenomenon of seismic energy generation-propagation. From an engineering point of view, the epicenter should be replaced, for instance, by the fault trace, corresponding to the locus of the projection at the surface of the probable initiation of the rupture.

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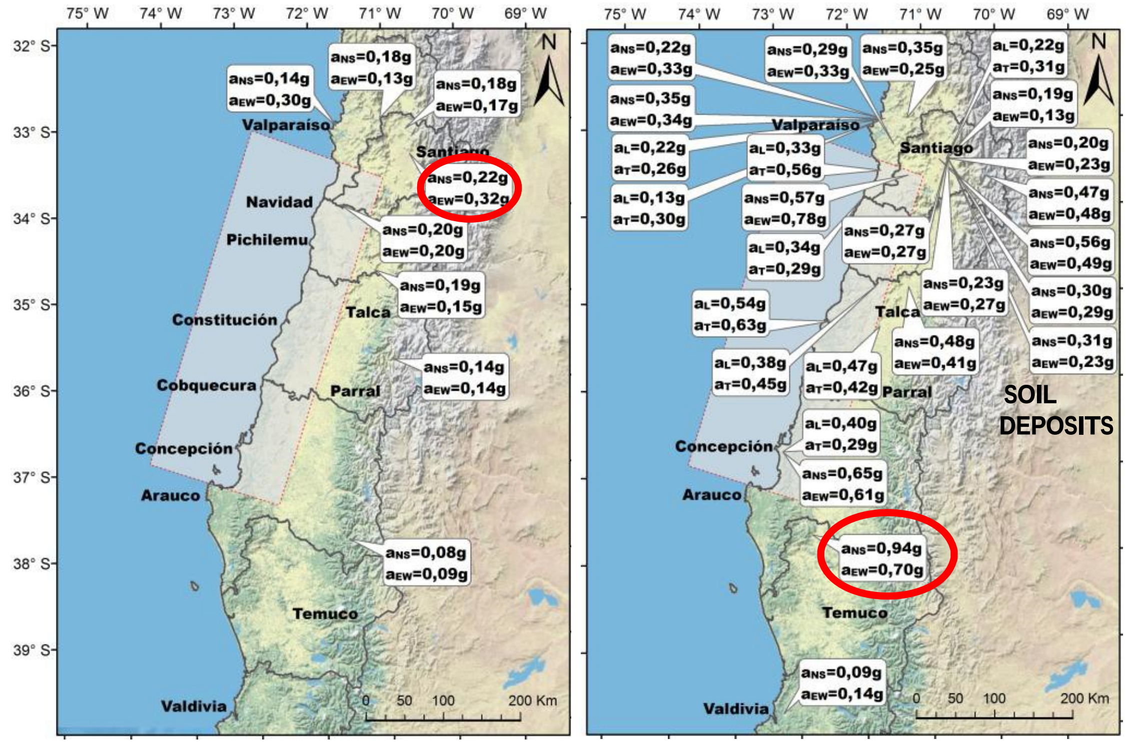

Fig. 1.- Horizontal PGA recorded on rock outcrops and soil deposits

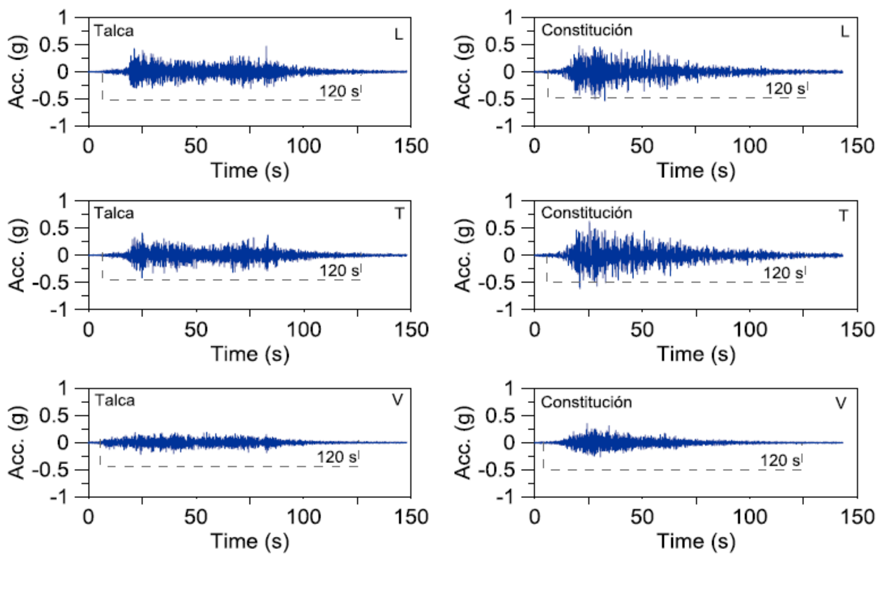

Fig. 2.- Acceleration time histories recorded in Talca and Constitucion (Renadic)

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2.- CLIMATOLOGICAL FACTOR

Most of the area that was strongly affected by the earthquake presents a high rate of rainfall during winter time (June to August), which controls the stability of the natural terrain. However, the summer season (December to March) is pretty dry, so at the time of the earthquake, most of the slopes were either dry, or at most, partially saturated, having consequently an extra cohesive resistance. This climatological factor may explain the reduced number of slope failures, although the intensity and duration of strong ground motion were severe.

3.- FAILURES OF HIGHWAY EMBANKMNT

There were several failures of highway embankments of well compacted fill (structural fill). The failures were caused by the existence of weak natural ground, which was neither appropriately investigated nor treated. Three typical examples of this type of geotechnical failure are shown in the photographs of Figs. 3 to 6.

Fig. 3.- Failure of a fill triggered by foundation failure. Cruce Villaseca, Km37-Ruta5

Fig. 4.- Failure of Paso Superior Copihue

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Fig. 5.- Failure of a fill triggered by foundation failure, Sector Polvorín, Ruta P160

Fig. 6.- Failure of the access at bridge Tubul

In all these cases, due to the abundance of native vegetation, the presence of a shallow water table was undoubtedly identified. Obviously, the well compacted gravelly materials that constituted the structural fills were not able to maintain the global stability, which was controlled by inappropriate foundation condition.

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4.- FAILURES OF TAILINGS DAMS

The waste products resulting from mining operations are called tailings. Typically, in copper mines, the extracted ore is crushed to the size of fine sand to clay from which the minerals are recovered. In the case of Chilean copper mines, around one percent in weight corresponds to the valuable mineral, so a huge amount of tailings is produced, which are usually deposited in the so-called tailings dams.

In the area affected by the strong motion, there are eight major tailings dams that seismically performed well. However, out of more than 50 small to medium tailings dams, five developed seismic failures. Limited seismic displacements were experienced by four tailings dams, without major problems. Unfortunately, one tailings dam underwent flow failure (liquefaction) that resulted in four fatalities (Verdugo et al, 2012). In the photographs presented in Fig. 7 the mass of tailings remaining after the flow can be observed. Therefore, considering the significant number of tailings dams existing in the area, it is possible to indicate that in general the seismic behavior was almost optimum with only one catastrophic failure.

Fig. 7.- Mass of tailings remaining after flow failure

5.- DAMAGES INDUCED BY SOIL LIQUEFACTION

Field observations have shown that the earthquake triggered liquefaction in more than 100 different sites, whose distribution is presented in Fig. 8. The northernmost site with evidence of liquefaction corresponds to the deformation experienced by the slope of Veta del Agua tailings dam (located approximately 13 km north-east of La Calera), while the southernmost liquefied site occurred in Calafquén Lakes (located 250 km to the south of the rupture zone) and the city of Valdivia. Consequently, the area with evidence of liquefaction covers a north-south distance of about 800 km, which corresponds to an area close to twice the rupture zone.

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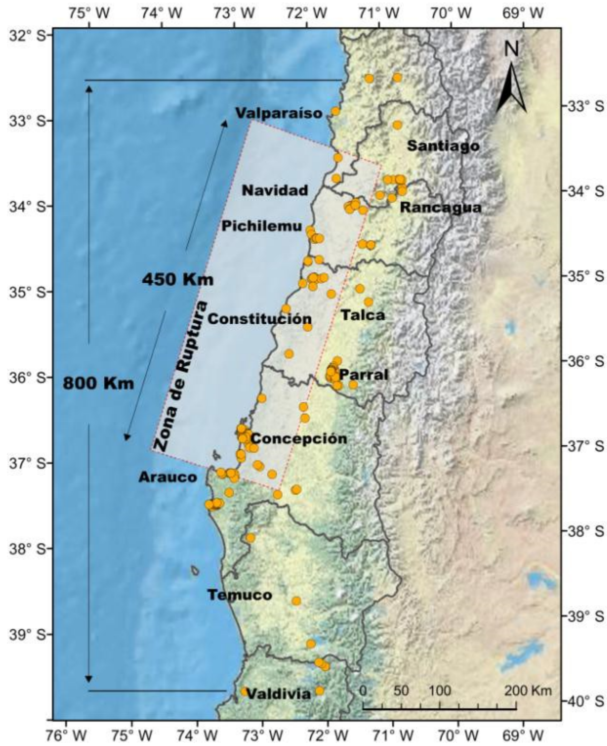

Fig. 8.- Site where liquefaction was observed

The phenomenon of lateral spreading was extensively observed in the vicinity of rivers and lakes, as shown in Fig. 9. In the area of Licanten, Mataquito River, the length of the cracks associated with this mechanism reached about 2000 m, involving displacements and settlements to a distance that exceeded 100 m from the border of the river.

Fig. 9.- Lateral spreading observed in Calafquén Lake and Nancagua

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Significant settlements developed after liquefaction was observed at many places along the railway system as shown in Fig 10. Because of this type of failures the transport by this system was stopped for several weeks after the earthquake, with an additional impact on the post seismic recovery of the country.

Fig. 10.- Settlements after liquefaction, near city of Concepcion (courtesy of EFE)

The city of Concepcion is founded on deep sandy soil deposits, with a water table at 3 m to 7 m below the natural surface. Although most of the deposits consist of dense sandy materials, some of them are loose enough to have experienced liquefaction, affecting routes, bridges, houses and buildings. Examples of these failures associated with the phenomenon of liquefaction are presented in Figs. 11 to 14. The large displacements observed in the failure of Fig. 12 occurred in the city of Constitucion.

Fig. 11.- Route Costanera Norte BioBio

Fig. 12.- House in Talcahuano

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Fig. 13.- Differential settlements observed along Juan Pablo II Bridge, Concepcion

Fig. 14.- Failure observed in Constitucion city

The damages caused by liquefaction in port facilities were especially important because of their economic impact. The most typical failure was the lateral displacement experienced by piles embedded in laterally spreading ground. Some of these failures are shown in Figs. 15 to 18.

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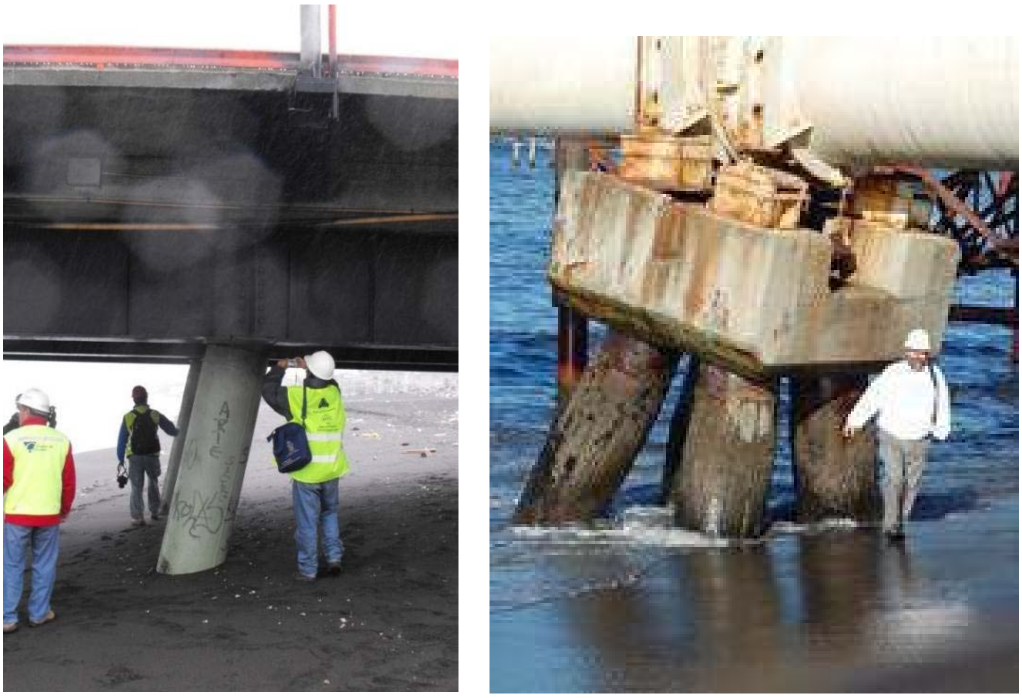

Fig. 15.- Pile tilted by the lateral movements of liquefied soil, Coronel, Bocamina

Fig. 16.- Large displacements experienced by a pier of local fishers

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Fig. 17.- Evidence of the lateral displacements experienced by the liquefied ground

Fig. 18.- Quay wall in La Poza, Talcahuano

In San Vicente Bay a fishing industry made its facilities on a platform built on reclaimed land. The platform sank dozens of centimeters and moved towards the sea, destroying most of the facilities (Figs. 19 and 20). The limited available information indicates that the natural ground consists of loose sandy soil deposits and mud (materials that would not have been removed or improved) and this is an undesirable condition that may explain the observed failure.

Another clear evidence of liquefaction was the uplift of buried structures such as tanks and manholes, as shown in Fig. 21.

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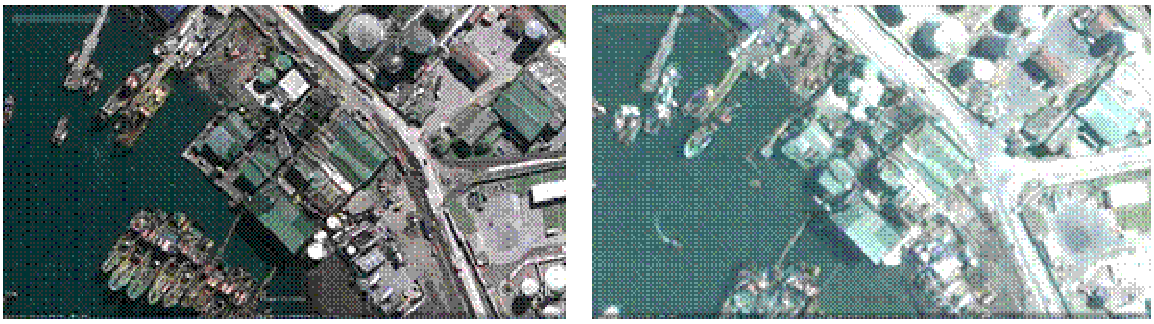

Fig. 19.- Liquefaction failure of a reclaimed land (before and after failure)

Fig. 20.- Sinking of the reclaimed land under the sea

Fig.- 21.- Uplift of buried structures (Chillán and Arauco)

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6.- CONCLUDING REMARKS

The February 27, 2010 Chile earthquake, of Magnitude 8.8, had a rectangular rupture zone of approximately 450 km by 170 km, whose effects covered more than 800 km of the central-south part of Chile. The seismic records show that the shaking lasted close to two minutes. After the earthquake a tsunami devastated parts of the coast killing and destroying towns. The official reports indicate less than 600 victims and the estimated economic loss would be near 30 billion US dollars.

Structural damages observed in some building were attributed to site effects. In this regard, the official Chilean seismic code at the time of the earthquake classified the sites, investigating the upper 20 m of the ground, according to soil parameters mainly associated with their resistance, such as RQD, unconfined strength, SPT-N, and undrained strength. This approach resulted in several sites that were incorrectly classified, underestimating their response spectra, especially in cases of deep soil deposits of sandy or clayey materials.

The geotechnical failures caused by the 2010 Chile Earthquake are in the framework of the present engineering knowledge and, in general, are associated with a poor investigation and inadequate design.

Concrete, earth and tailings dams performed well, except a catastrophic collapse of one tailings dam that caused four casualties. The occurrence of landslides was minor, which is explained by the extra cohesive resistance of the soils. The earthquake hit the area at the end of the dry season.

Following the experience left by large earthquakes, liquefaction phenomenon occurred at many sites, causing damage to the road infrastructure, railroads system, ports, buildings and houses. Liquefaction-induced ground failure displaced and distorted pile foundations of piers impacting seriously the operation of some ports.

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