Geogr. Fis. Dinam. Quat.
38 (2015), 3-13, 14 figg., 1 tab.

DOI 10.4461/GFDQ.2015.38.01

ARTURO BELMONTE (*), EDILIA JAQUE (**), JORGE QUEZADA (***), ALFONSO FERNÁNDEZ (**),
CECILIA DONOSO (****) & CARLOS CARTEAU (*****)

SITE EFFECTS ASSOCIATED WITH THE 2010 MAULE EARTHQUAKE IN ZONES CHARACTERIZED BY THE PRESENCE OF WETLANDS IN THE BIOBIO REGION, CHILE

ABSTRACT: BELMONTE A, JAQUE E., QUEZADA J., FERNANDÉZ A., DONOSO C. & CARTEAU C. *Site effects associated with the 2010 maule earthquake in zones characterized by the presence of wetlands in the Biobio Region,Chile.* (IT ISSN 0391-9838, 2015).

After 2010 Maule (Chilean) earthquake (M_w=8.8, February 27th) some residential areas located along the coastal border in southern Chile and close to water bodies and wetlands showed extensive damage in housing, streets, electric, water, and gas lines. That was the case of the neighborhoods Villa Las Araucarias (Arauco) and Bayona (San Pedro), situated 100-170 km south of the epicenter zone, and established on top of a porous artificial filling and compacted soils. Conversely, in other sites soils and infrastructure remained intact. Here, we present a study that aimed to describe and assess the effects of the Maule earthquake on urban sites. We tried to disentangle the differences between damaged and undamaged zones by identifying modes of damage as well as by detecting geophysical anomalies associated with such a divergent behavior. For this reason, we also analyzed three undamaged zones: Colcura (Lota), Laguna Grande (San Pedro) and Los Canelos (San Pedro). Results suggest that the damaged locations behaved as examples of the liquefaction phenomenon, triggered by a large earthquake. The implications of this finding are discussed according to existing Chilean regulation in terms of the so-called V_{S30} parameter as a quality factor for soils. We also discuss different aspects related to the relationship between geophysical methodologies applied here, visual observations and geological/soil interpretation.

KEY WORDS: Soils, Wetland, Maule Earthquake, Electrical, Seismic and ReMi Methods, Chile.

RESUMEN: BELMONTE A, JAQUE E., QUEZADA J., FERNÁNDEZ A., DONOSO C. & CARTEAU C. *Efectos de Sitio asociados con el terremoto del Maule 2010 en zonas caracterizadas por la presencia de humedales en la región del Bío-Bío, Chile*. (IT ISSN 0391-9838, 2015).

Durante el terremoto del Maule (27/02/2010, M_w=8.8), el área centro sur de la Región del Biobío, Chile y en particular algunas zonas residenciales ubicadas a lo largo del borde costero y cerca de cuerpos de agua y humedales, mostraron grandes daños en viviendas, calles, instalaciones de electricidad, agua y líneas de gas. Ese fue el caso de los barrios Villa Las Araucarias (Arauco) y Bayona (San Pedro), situados a 100 y 170 km al sur de la zona del epicentro, establecidas sobre un relleno artificial poroso y suelos compactados. Por el contrario, en otros tipos de suelos la infraestructura permanecieron intactas.

A continuación, presentamos un estudio que tuvo como objetivo describir y evaluar los efectos del terremoto de Maule en sitios urbanos; tratamos de explicar las diferencias entre las zonas dañadas y no dañadas mediante la identificación de modos de daños, así como mediante la detección de anomalías geofísicas asociadas con tal comportamiento divergente. Por esta razón, también se analizó tres zonas no dañadas: Colcura (Lota), Laguna Grande (San Pedro) y Los Canelos (San Pedro). Los resultados sugieren que los lugares dañados se comportaron como ejemplos del fenómeno de licuefacción, provocada por un terremoto de gran magnitud. Las implicaciones de este hallazgo se analizan de acuerdo a la regulación chilena existente en términos del llamado parámetro V_{S30} como un factor de calidad de los suelos. También se discuten diferentes aspectos relacionados con la relación entre metodologías geofísicas aplicadas aquí, observaciones visuales y la interpretación geológica y de suelos.

PALABRAS CLAVE: Los suelos, Humedales, Maule Terremoto, Eléctricos, Sísmica y Métodos ReMi, Chile.

INTRODUCTION

Local geology can explain damage in small areas hit by earthquakes. Observations of site effects after a main seismic shock can provide insights into why some areas are strongly affected and how they could be qualified under geophysical measurements.

The February 27th, 2010 Chilean earthquake struck an extensive area in the central-south region of Chile (fig. 1)

(*) *Departamento de Geofísica, Facultad de Ciencias Físicas y Matemáticas, Universidad de Concepción, Casilla 160-C, Concepción, Chile, abelmonte@dgeo.udec.cl*

(**) *Departamento de Geografía, Facultad de Arquitectura, Urbanismo y Geografía, Universidad de Concepción, Casilla 160-C, Concepción, Chile, edjaque@udec.cl, alfernandez@udec.cl*

(***) *Departamento de Ciencias de la Tierra, Facultad de Ciencias Químicas, Universidad de Concepción, Chile, jquezad@udec.cl*

(****) *Servicio Nacional de Geología y Minería (Sernageomin), Av. Santa María 0104, Providencia, Santiago, Chile, cecilia.donoso@sernagoemin.cl*

(*****) *Consorcio Eólico, Av. Collao 1485, Concepción, Chile, carlos.carteau@gmail.com*

We want to thank a lot to Villa Las Araucarias' neighbors who welcomed us from the first moment and helped us to carry out the present work. Furthermore we wish to thank to Vicerrectoría de de Investigación de la Universidad de Concepción by financing geophysical measurements in frame of DIUC Project 211.012.011-1.0.

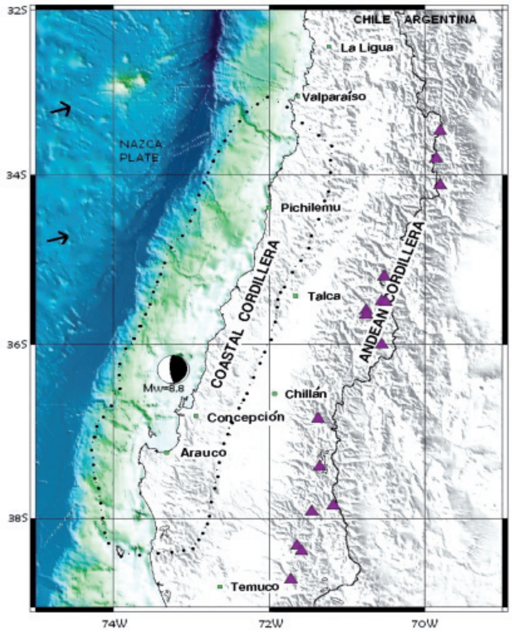


FIG. 1 - Location map of the 2010 Maule Earthquake (Mw=8.8) rupture area, including the epicenter and the focal mechanism (indicated by the so-called white and black "beach ball"). Black dots represent the actual rupture extent, the epicenter and the focal mechanism Cities (green squares), volcanoes (purple triangles), geomorphological units (Coastal and Andean Cordillera) as well as direction of Nazca Plate with respect to South American Plate (black arrows) are also included. Concepción and Arauco are located in the southern section of the earthquake rupture plane. The earthquake mechanism is associated with a thrust event.

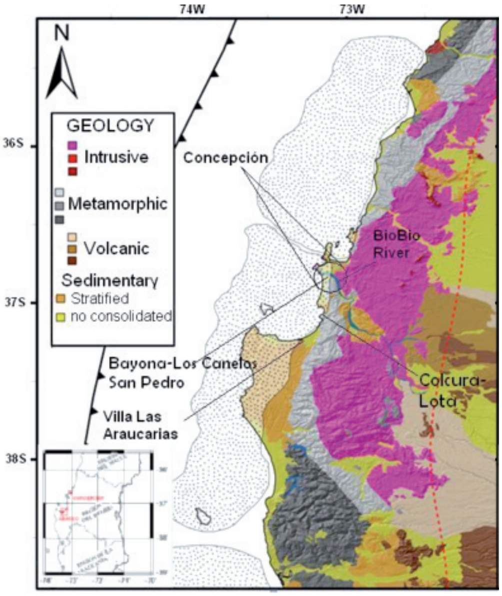


FIG. 2 - Geological map of BioBio Region coastal border. Villa Las Araucarias (Arauco) as well as Bayona (San Pedro) and Los Canelos (San Pedro) are shown, all located in areas featured by non-consolidated sediments. Colcura (Lota), where metamorphic basement crops out, is also included. The BioBio River can be seen down to its river mouth. The Laja River has its river mouth about 60 km south-east of the BioBio river mouth. Intrusive and metamorphic outcrops as well as volcanic rocks are related to the so-called Cordillera de la Costa which south of Concepción is known as Cordillera de Nahuelbuta.

where a number of events (M>8) have left their mark since the Spaniards arrived in Chile: 1575, 1657, 1751, and 1835. This region was considered a well-known seismic gap zone (Barrientos, 1994; Quezada & *alii*, 2010).

Although the destructive capacity of a main shock is often proportional to its magnitude and distance from the rupture zone (Kramer, 1996; Verdugo & *alii*, 2010; Bertalot, 2011), the largest level of destruction observed after the 2010 main shock was distributed along sites characterized by 10 to 15 year-old artificial fillings situated close to and/or on the top of wetlands (in Spanish *humedal*) whose origin dates from the Holocene – late Pleistocene time-span and whose peculiarity consists of high levels of water saturation. A high water-saturated soil is more susceptible to liquefaction in cases of Holocene sandy deposits (Youd & Hoose, 1977) and sediments of similar grain-size, packed in layers thicker than 1 m. Furthermore, some man-made artificial fillings subjected to compacting technics have also proven to be highly susceptible to the liquefaction phenomenon.

Quake shaking produces an increase of water pressure on pores, associated to soils with loamy-sandy content, reducing effective stress and shear resistance of sand (Obando, 2009). Therefore, material behaves as liquid giving rise to vertical and horizontal motion, which turns into displacements and/or large settlements. This process is known as induced liquefaction and it is one of the main causes of high urban seismic risk. A relevant and necessary condition for a site to show such behavior is the presence both of high water content in the subsurface (extending more than 3-5 m deep) and low-grade compacting. According to Verdugot& *alii*. (2010), low water table levels, a usual condition during the dry season, prevented more intense and extensive damage during and after the Maule Earthquake.

Our main objective is to describe and assess the effects of the Maule earthquake on urban sites. In our work, we link both geology and soil response to the main shock observed effects with geophysical parameters such as conductivity/resistivity and seismic waves propagation velocity.

GEOLOGIC AND GEOMORPHIC FRAMEWORK

The study area is located south of the Bio Bio River. Here, a northward, open embayment known as Arauco Gulf characterizes the Chilean coastal border. Block faulting produced a geomorphological structure characterized by a sandy plain at the top of Mesozoic-Cenozoic unit downthrown in a graben-like structure. Such a structure is bordered to the east by the fault scarp of the Coastal Cordillera and to the west by a similar type of steep slopes known as Arauco Peninsula (Galli, 1967).

The littoral zone of Arauco Gulf is a Coastal Plain, a flat area composed by Holocene sands (Kaizuka & *alii*, 1973; Islat& *alii*, 2012). Its extension varies between a hundred of meters to four kilometers with maximum heights of a few meters. The eastern border of the Coastal Plain (the Coastal Cordillera) is composed in their westernmost part by Pleistocene marine terraces (Kaizuka & *alii*, 1973). These terraces are also exposed along the border of the Coastal Plain located in the southernmost shoreline where the city of Arauco is located. A fossil cliff of 40-70 m height separates the younger Pleistocene terrace of Coastal Cordillera from the Holocene Coastal Plain.

Metamorphic and sedimentary rocks constitute the basement of the Coastal, emerging as outcrops along the Coastal Cordillera (fig. 2). Metamorphic rocks are phylites formed in the Carboniferous age. A high degree of weathering affects such rocks generating red clay. Normal faulting with NE-SW strike affects rocks located on the Arauco Peninsula and the Coastal Cordillera, generating tilted blocks.

This morphostructural setting favoured the creation of a coastal-alluvial plain constituted by thick sand deposits over which present-day wetland systems developed. Holocene sands belonging to the Coastal Plain have different composition. From Biobio River until Coronel (including San Pedro) they are black. Galli (1967) named these unconsolidated deposits as Huachipato Formation, characterized by fine to medium sands with clasts of basaltic composition. These sands came from the volcanic activity located at the high Río Laja Valley during the Late Pleistocene and Holocene. They were first carried down to the palaeo-coastline through the Laja and Bio Bio Rivers (Ilabaca, 1989; Mardones & Jaque, 1998; Mardones, 2005) and then reworked and deposited southwards in the direction of the Arauco Gulf. South Coronel city including the Arauco area, the sands are fine with light colors and came from small rivers from Coastal Cordillera and reworked by the sea forming succesive beaches.

The Biobio region in southern Chile presents about 17 large size wetlands and another 30 of smaller sizes along the coastal border (Gonzales & Victoriano, 2005). Between the cities of Talcahuano and Arauco wetland areas have been covered by urban expansion that has both occupied their surfaces and transformed the surficial sediments in those sites.

The most important wetlands in the study are Los Batros and Arauco. Los Batros wetland is located at San Pedro between the Coastal Cordillera and Biobio River. Its extension reaches up to 2 km from Laguna Grande Lake to Biobio River (fig. 2). Here several branched natural fluvial streams have been filled with sand for building residential areas. The Arauco wetland area is located along the Laraquete-Arauco Plain, associated to the Carampangue River, at the eastern border of Arauco city. The Arauco wetland area reaches up to 4 km^2 (figs. 2 and 3). Las Araucarias place are located above this wetland over an unconsolidated, man-made filling deposit.

STUDY SITES

During inter-seismic cycles (i.e. normal times for the population) any new residential area tends to cover previous landscapes and landforms, making more difficult to estimate the potential risk associated with the way that soil will behave under strong seismic shaking. That is the case for Villa Las Araucarias in Arauco and Bayona in San Pedro, among others. In this study, we focused in these two areas as example of damaged locations.

Villa Las Araucarias was built in 1995 after a new urban zoning plan had been created in 1988, allowing occupation of a section of an extensive wetland area (Carampangue) (figs. 2 and 3). A similar zoning plan permitted the urban expansion and construction of residential areas in Bayona.

We also studied locations apparently unaffected by the 2010 earthquake, because they are situated over more consolidated sites. More specifically, we analyzed Los Canelos and Laguna Grande in San Pedro as well as Colcura in Lota (midway between Arauco and San Pedro). Los Canelos is situated above an apparently well-compacted filling soil, out of the perimeter of the San Pedro wetland. Laguna Grande and Colcura lie on a weathered metamorphic basement.

METHODOLOGY

Shortly after the February 27th Earthquake, on March 17th, we carried out field visits to Bayona and Villa Las Araucarias. From these two locations, we performed de-

Fig. 3 - Specific location of Bayona, Los Canelos and Laguna Grande in San Pedro (left) and Villa Las Araucarias in Arauco (right) are shown. In both pictures it is possible to see wetland areas related to suburban zones (modified Google Map Images).

tailed analysis in Villa Las Araucarias, where we dug two soil pits, allowing us to obtain information on the type, quality, and compactness of soil. In Bayona, we could record field observations and photographs only.

We also determined electrical and seismic profiles: Vertical Electric Sounding (VES/Schlumberger), Dipole-Dipole, Refraction Seismic, and ReMi Method (see Appendix 1). For resistivity and velocity measurements, in addition to the Villa Las Araucarias site, we sampled three other sites to characterize areas with no earthquake damage. (Donoso, 2011, Carteau, 2013): Colcura (Lota), Laguna Grande (San Pedro) and Los Canelos (San Pedro). We aim to establish a reference for geophysical parameters in wetland areas as well as to quantify the expected contrast.

RESULTS

Field observations

Places under observation reach dimensions of a few hundreds of meters per side. Sites without damage must be understood as places where houses, play-ground squares, pavement streets and services resulted with minor to no damage after main shock. Field observations concentrated in Villa Las Araucarias and Bayona. They enabled us to recognize deformations and damages that we could associate as closely related to liquefaction phenomena. Theoretically, liquefaction phenomena triggered by earthquakes can affect buildings, housing, bridges, streets and pipes in the following different ways: settlement, lateral spread, cracking along streets, sand boils and stability failures. Field observations show clearly evidence for such effects after the main shock, with exception of sand boils which can be expected in more saturated soils than those present in the summer season.

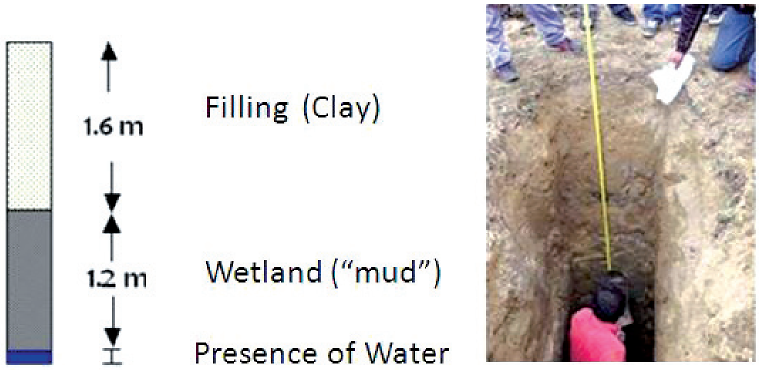
We distinguish: (a) irregular failure concentrated along streets and houses with extensions of 20 to 40 cm, and consequences such as asphalt blocks removed; (b) lateral spread towards existing filling's free faces which generated extensive cracking up to 20 cm thick inside the houses, located around two meters from the filling´s border; (c) systematic cracking along streets; (d) inside the houses, cement floor (0.5-1 meter thick) settled up to 10 cm with respect to parking and/or gardens. Figure 4 shows pictures where these features are evident.

Field test and filling characteristics

Field tests were carried out on two soil pits caved in Villa Las Araucarias*,* for both anthropic filling and wetland mate-

Fig. 4 - In Villa Las Araucarias, (A) failure and removed blocks, (B, C) lateral spread outside and inside houses. In Bayona, (D) an uplifted sewer cylinder terrain due to soil settlement, (E) irregular settlement, (F) floor uprising within a house, (G) extensive lateral spread along a recreational sector, (F) abrupt longitudinal uprising.

Fig. 5 - On the left a description of the profile observed in one of the soil pits in Villa Las Araucarias neighborhood is shown. On the right the corresponding soil pit is also shown.



rial showing differences in resistance when pressure was exerted on the material. While pressure on a handful of filling disintegrated the sample into particles of different grain size, the same exercise on wetland muddy material deformed malleably without producing any fracture or relevant humidity release. This simple field test indicates that both materials behaved in different ways during the main shock, thus being a possible cause of fissures generated up to the surface. Soil pit itself revealed a filling characterized almost entirely of clay, some sand and wood pieces. Observed filling extends down to a depth of 160 cm, below which mud associated to wetland material extends for another 120 cm down to reach water apparently linked to wetland (fig. 5).

Type of deformation

A sketch trying to recreate observations on deformation is shown in Figure 6. The shallower layer can be fractured into blocks that are separated through fissures which open and close during quake shaking. Settlement of structures and housing is associated to the redistribution of porous fluid during and after quake shaking, generating material that compacts itself. This effect produces both concentration of deformation at structures based on superficial foundations and damage in piping systems. Consequently, large cracking is observed after the main shock has occurred. Lateral spread effects produce the breaking up of shallow layers into blocks which move progressively towards a so-called free face or downhill. Such deformations can vary from a few centimeters up to 2 m. These are consequence of inappropriate artificial filling. In fact, man-made comprehensive filling should be the best soil stabilizer. For residential areas the appropriate grain mixture should be formed by 0 to 40 mm diameter grain size, that is, sand, clay (in 40-50% proportion) and gravel. Pieces of wood in artificial fillings are forbidden, because their porous decomposition negatively influences the degree of compacting.

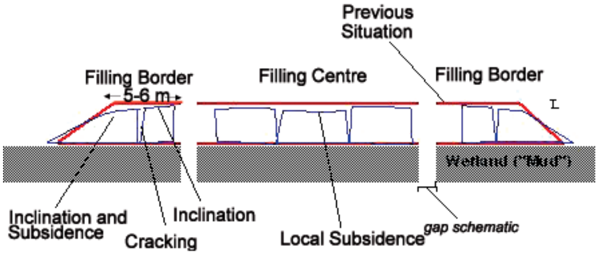


Fig. 6 - In blue color a sketch giving a possible form to deformations observed in surface at Villa Las Araucarias neighborhood. This sketch is deduced from field and soil pits observations. Red line shows the original state (before the main shock).

APPLICATION OF GEOPHYSICAL METHODS

Geoelectric survey

A total of three VES profiles and one Dipole-Dipole profile were carried out, both in Villa Las Araucarias, Colcura and Laguna Grande (San Pedro). Our aim is to establish evidence of some expected contrast in resistivity according to their geologic/soil properties compared to the main area of study in Villa Las Araucarias (fig. 7).

Three clear changes of slope can be detected from the plot $\log_{10} \varrho$ [Ohm-m] v/s $\log_{10}$ depth [m] (fig. 8), which can be associated with two layers and infinite half-space. In Villa Las Araucarias the first meter of depth is linked to resistivity values of about 60 [Ohm-m], then a decrease down to 10 [Ohm-m] is observed for the next 3 m of depth associated possibly with the presence of water and finally a strong increased resistivity ranging up to orders of 10^3 [Ohm-m] is clearly marked. In spite of finding similar shaped curves for other two VES profiles in Colcura and Laguna Grande, the lowest part extends no lower than 150-200 [Ohm-m].

The first 5 m of the Dipole-Dipole profile in Villa Las Araucarias reveals resistivity values ranging from 1 – 200 [Ohm-m]. Minimum values coincide with the place where the soil pit was dug. At depths of 5 to 6 meters, resistivity increases apparently due to the presence of sandstone or sand associated with Tubul Formation.

Seismic refraction and refraction microtremor (ReMi)

In Los Canelos one ReMi and Seismic Refraction line consisting of 23 geophones (14 Hz) every 4 m was displayed

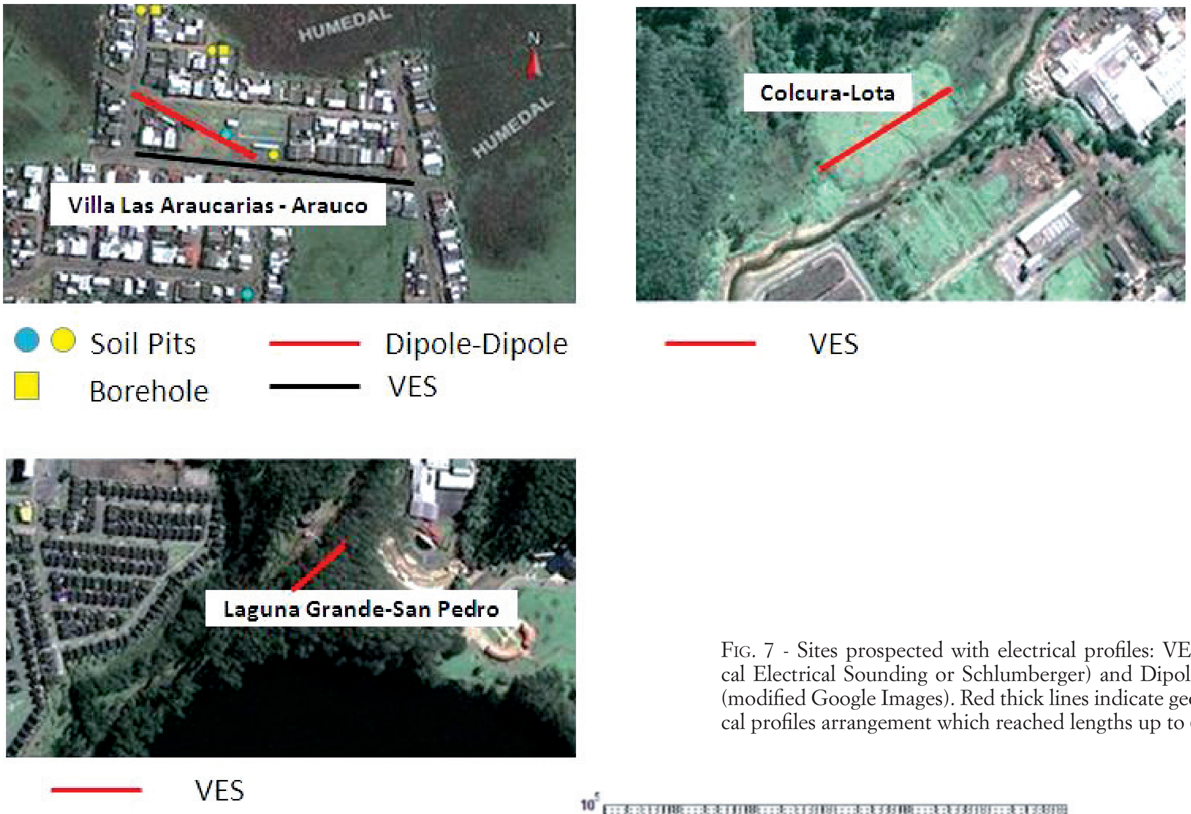


FIG. 7 - Sites prospected with electrical profiles: VES (Vertical Electrical Sounding or Schlumberger) and Dipole-Dipole (modified Google Images). Red thick lines indicate geo-electrical profiles arrangement which reached lengths up to 60-80 m.

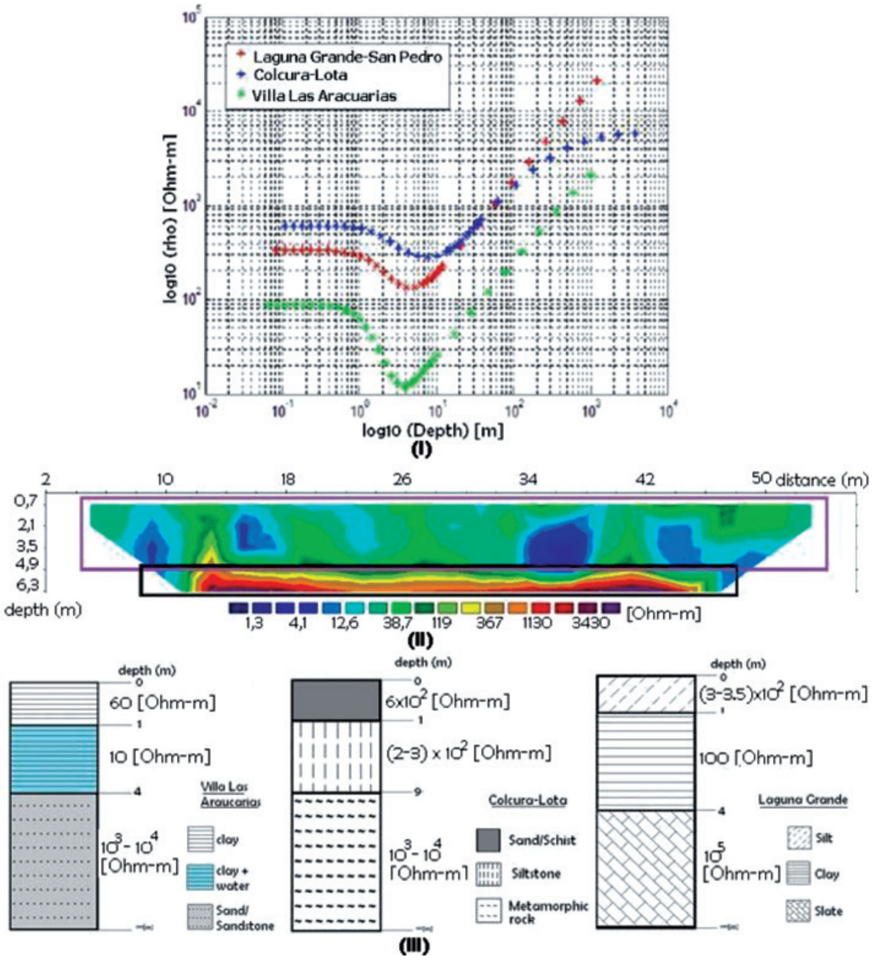


FIG. 8 - Resistivity results and stratigraphic interpretation are shown here. From top to down: (I) Schlumberger profiles (VES) results plotted as $\log_{10}$ ϱ [Ohm-m] v/s $\log_{10}$ Depth [m] for 3 field sites: Villa Las Araucarias, Colcura and Laguna Grande, (II) 2-D Dipole-Dipole resistivity section for Villa Las Araucarias profile and (III) stratigraphic interpretation for all three sites.

FIG. 9 - On the left location for seismic refraction profile in Los Canelos (San Pedro); one the right ReMi and seismic refraction profiles displayed in Villa Las Araucarias (Arauco) are shown (modified Google Images).

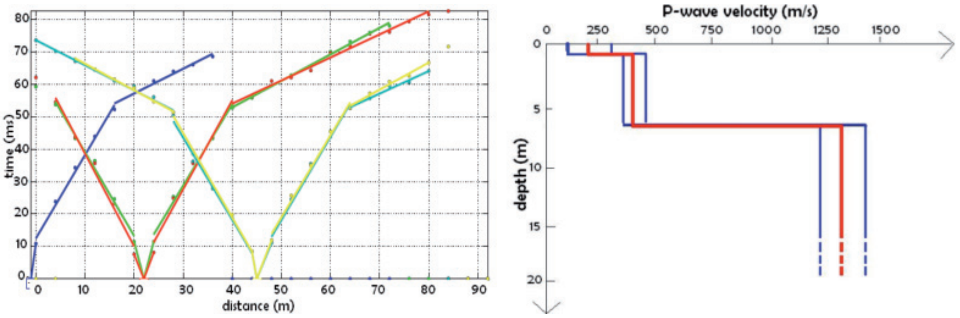


FIG. 10 - Los Canelos. On the left seismic refraction travel times are shown together distinct interpretation curves represented by different colors. On the right hand 1-D velocity models is shown (VP[m/s] v/s h[m] plot). In red color the average value which deviation is marked by blue color lines.

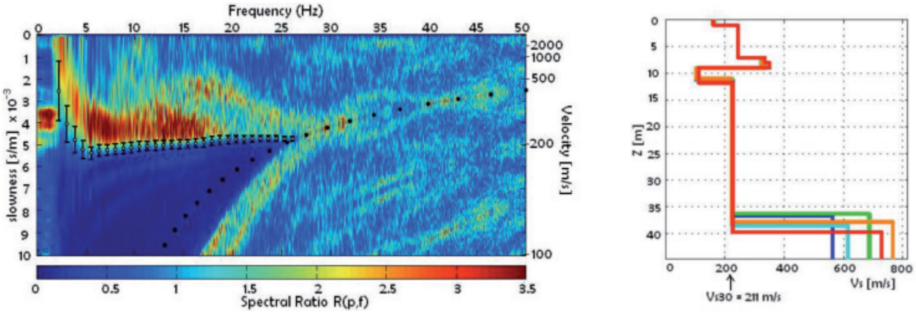


FIG. 11 - Los Canelos. On the left hand spectral ratio and chosen dispersion curve is shown. On the right hand inversion results for six best iterations (S-wave velocity [m/s] v/s depth [m]) are exposed as 1-D S-wave velocity models. Vs30 is the S-wave velocity average for first 30 meters (df=0.03125 Hz, dp=0.0001 s/m and np=101).

along 88 m length while that in Villa Las Araucarias two ReMi and Seismic Refraction lines consisting of 17 geophones (4.5 and 14 Hz) every 4 m were carried out along 64 m length (fig. 9).

In Los Canelos, seismic refraction travel times were adjusted to a model with two layers above an infinite half-space. Maximum, media and minimum resulting model velocities are shown in Figure 10.

For ReMi profiles main noise source can be assigned to vehicular traffic. Combining 3 recordings it was possible to obtain a clear descending signal. Several inversions were carried out for a frequency range 3 to 26 Hz. Three first layers were constrained to P-wave velocity obtained from seismic refraction experiment. Density was taken as 2000 kg/m^3 and a Poisson coefficient between 0 and 0.5. In Figure 11 spectral ratio (see Appendix 1) and 1-D S-wave velocity model are shown.

A thin first layer is associated to vegetation cover (Vp ~ 240 m/s; Vs ~ 180 m/s), only detectable with seismic refraction experiment. The next two lower layers are associated to typical values for both dry and wet sands (Vp ~ 430 m/s; Vs ~ 220 – 340 m/s). These sediments can be classified as fine to thick silty clay, which would also be coherent with the geologically known BioBio sands in San Pedro. Lowering of S-wave velocity around 10 m depth (Vs ~ 150 m/s) could be associated with a prior vegetation cover inserted into the BioBio sands sequence. V_{S30} parameter is estimated as V_{S30} ~ 211 m/s, which according to modified NCh433 of96 (Chil-

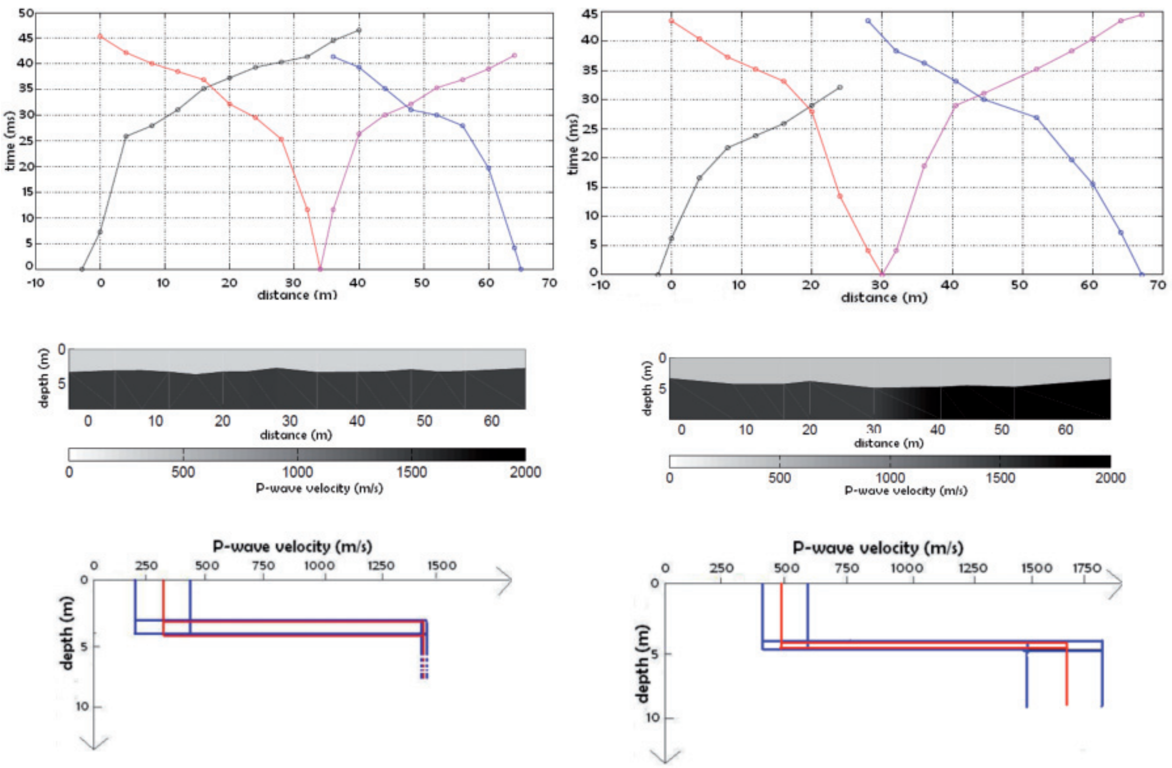


Fig. 12 - Villa Las Araucarias. On the left and right respectively plots related with VILLA 1 and VILLA 2 are exposed. On top seismic refraction travel times and fit curves. On the middle 1-layer velocity model using delay time method is sketched. On the lower part resulting 1-D velocity models are shown. Here red color lines indicates an average value; deviation is shown by blue color line.

ean regulation for Seismic Building Design, 1996) would be related with a soil type D, that is, moderately dense and solid (see also Appendix 1).

In Villa Las Araucarias, two profiles could be arranged: VILLA 1 and VILLA 2. In both cases two shots in the borders and one shot in the mid-section allowed to using the so-called delay time method for seismic refraction profiles. Figure 12 presents travel time data as well as one layer with a half-space model.

For ReMi profiles main sources of noise area associated to vehicular traffic and near construction as well as forest activity. For VILLA 1 and VILLA 2 a descending trend for dispersion selected curve can be observed in range of 5 to 16 Hz. Firsts layers were constrained to P-wave velocity obtained from seismic refraction experiment. In the same way as for Los Canelos profiles, density was taken as 2000 kg/m^3 and a Poisson coefficient variable between 0 and 0.5.

Integrating VILLA 1 and VILLA 2 (fig. 13), it is possible to identify a first layer reaching down to 4-5 meters with velocities associated with vegetable covering and clay (Vp ~ 300-500 m/s; Vs ~ 120-140 m/s). As we know from soil pits observations, this layer contains 2 sub-layers: artificial filling and a (wet) mud containing clay and sand. Apparently, a second layer with Vs ~ 210-280 m/s is thicker in VILLA 2 than VILLA 1, which could be related with wetland distribution below the artificial filling. A third layer below around 20 meters depth can be assigned with Vs ~ 400 m/s associated possibly with sands. A fourth layer can only be seen in VILLA 1 with Vs ~ 600 m/s and could be related with a more rigid material as the Tubul Formation sandstone. In both profiles V_{S30} ~ 230-280 m/s which is associated with soils classification D.

DISCUSSION

Field observations and geophysical results appear to lead to some global expected relationships such as wetland areas tend to present both low resistivity and low S-wave velocity values, that is, artificial fillings above wetlands present low soil quality factor in light of geophysical parameters. However, some particular aspects look contradictory as well as new.

The first aspect is related with seismic measurements. They show that differences between sites like Villa Las Araucarias and Los Canelos do not diverge as much as expected in light of damage observed on each place. According to V_{S30} estimations, both soils fall in same category, namely moderately dense and solid type D. Then we estimated average velocity in the whole range from 0 to 30 m depth (fig. 14). Although at 30 m depth average velocity is smaller in Los Canelos than in Villa Las Araucarias, the opposite situation occurs in the superficial layer. That is, extreme low average S-wave velocities characterize shallow range of depths (z < 10 meters). In comparison to places without damage,

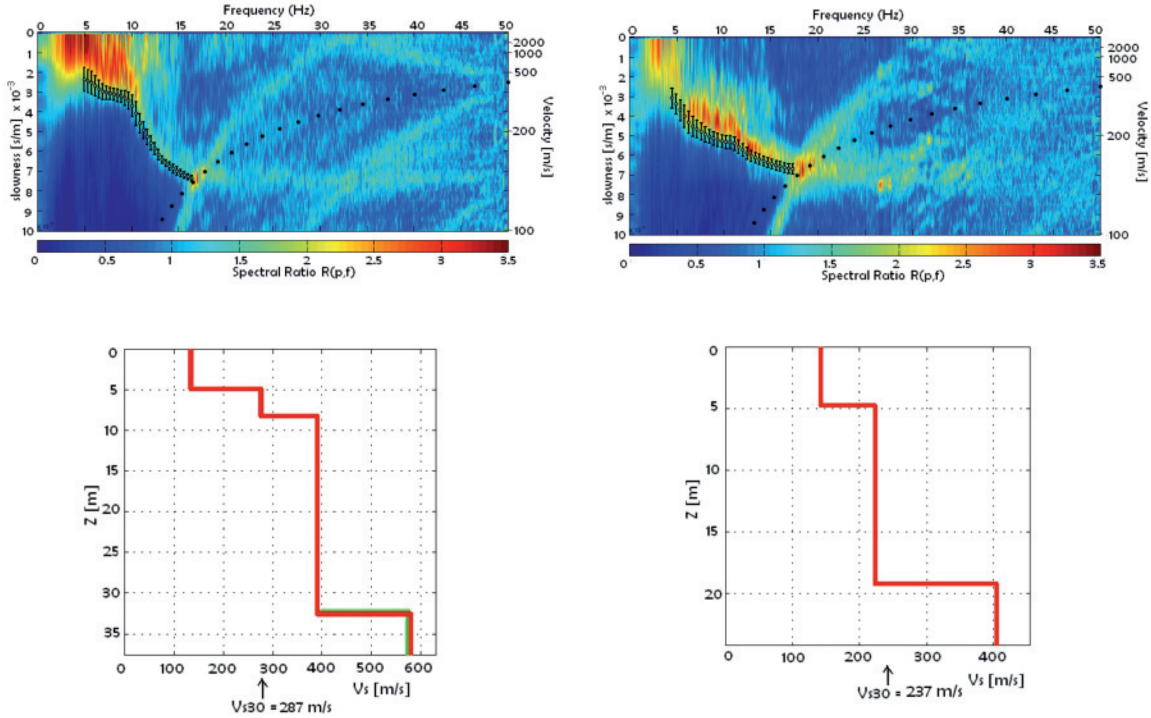


Fig. 13 - Villa Las Aracuarias. On the left hand spectral Ratio, chosen dispersion curves and 1-D S-wave velocity model for VILLA 1 are shown. Respectively on the right same plots and graphs for VILLA 2 are displayed. Vs30 is the S-wave velocity average for first 30 meters. (df=0.0333 Hz, dp=0.0001 s/m and np=101).

like Los Canelos, such low S-wave velocity would clearly be in correlation with consequences observed in Villa Las Araucarias after 2010 Earthquake.

This implies that the V_{S30} parameter may not be an accurate soil-quality index. Although the modified Chilean law (NCh433 of96) should describe places like Villa Las Araucarias as a "collapsible soil" assigning it into a category of "special type of soil", urbanism and building expansion tends to cover original landscapes with new human settlements making not obvious the identification of such classification soil type.

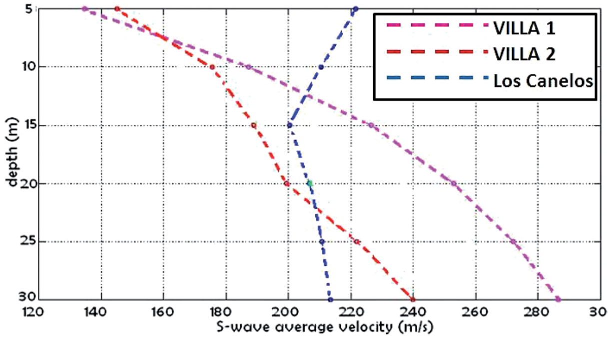


Fig. 14 - For each profile (Los Canelos and Villa Las Araucarias), S-wave average velocities for distinct range of depth are shown. At 30 meters depth we reach the corresponding Vs30 value.

A second aspect is related to the very thin low S-wave velocity "layer" observed in Los Canelos. Although it is not possible to generalize this observation, the fact that Los Canelos itself does not lie over a much more compacted soil according to S-wave velocity arises the question whether it would be possible that this low velocity anomaly attenuates incident waves in comparison to the permanent increasing velocity distribution with depth as in Villa Las Araucarias. It is known and demonstrable- for Love waves- that interfaces separating 2 layers with velocity increasing with depth are expected to show amplification in amplitude for incident waves coming from the bottom. This aspect requires further research.

Regarding to resistivity values obtained a goo, and expecte, correlation appears between low resistivity (10-30

Table. 1

TYPE	DESCRIPTION	V_{S30}[m/s]
A	Rock, compacted soil.	≥ 900
B	Soft or fractured rock, very dense and solid soil.	≥ 500
C	Dense and solid soil.	≥ 350
D	Moderately dense and solid soil.	≥ 180
E	Weak of soft soil.	< 180
F	Special soil.	-

[Ohm-m]) and areas damaged. The first meter of depth in Villa Las Araucarias appears related with ϱ ~ 60 (Ohm-m) and then a second layer down to 4 m with resistivity values around 10-30 (Ohm-m). These first depths appear to be related with extreme low S-wave velocities (Vs ~120-140 m/s) suggesting (VILLA 1 profile) a material particularly not very dense with presence of water. The increase of S-wave velocity below 4 m depth up to 400 m/s shows a correlation with resistivity value of order 3.

In comparison with sites where a more compacted soil gives form to subsurface (mainly constituted by metamorphic basement complex), orders are 1 to 2 greater compared to muddy-sandy soils. Such higher orders of magnitude for resistivity characterize well almost the whole electrical profiles in sites like Colcura and Laguna Grande. Although no electrical profile was performed in Los Canelos and no seismic profiles were performed in Colcura and Laguna Grande, it is possible to link them since they did not show damage after Maule Earthquake.

CONCLUSIONS

Resistivity values as low as 10 (Ohm-m) - in first 5 to 4 m depth - clearly indicate a close relation with both (1) low S-wave velocities and (2) severe damage caused by strong motion. So, the logs from Villa Las Araucarias indicate its link to a layer with high amount of water and in consequence with a weaker geotechnical soil material. Here the first meter depth is formed by a clay layer and then 4 m of clay with water. Below this depth sandstones and sand appear to be present.

Adding visual observations, hand-man test and linking it with role of wetland areas in both Villa Las Araucarias-Arauco and Bayona-San Pedro, it is possible to affirm that both locations behaved as examples of the liquefaction phenomenon triggered by a large earthquake. Verdugo (2010) had already recognized the liquefaction phenomenon in and around Concepción, indicating that replacing soft and weak soil with compacted sandy filling did not conduct to prevent liquefaction. Non-cohesive soil foundations saturated with water added to seismic strong motion lead to land faulting and cracking.

Apparently in the first 3 to 5 m depth two mechanisms appear to have main control over observed damage: (1) cracking and settlement appear to be produced due to decoupling of the upper from the lower layer. A 2 to 3 m thick layer constitutes a highly susceptible zone to liquefy and therefore it provides conditions to cause systematic fissures in the upper crust causing the asphalt and cement floor to become disaggregated into blocks; (2) lateral spread of fillings border where a free face (without any resistance to horizontal displacement) induces horizontal opening and cracking.

A reason for such effects is often related to a decoupling process between a deeper layer susceptible to liquefaction and a compact superficial layer, in this case, the artificial filling. Geophysical evidence shows a very low S-wave velocity as well as a decoupling in resistivity values in first 5 m depth. Conversely, a more homogeneous S-wave velocity value in shallow depths, even with low value as observed in Los Canelos, could result in a more efficient system to dissipate strong motion energy resulting in no observed damage.

REFERENCES

Barrientos S. (1994) - *Large Events, Seismic Gaps and Stress Diffusion in Central Chile, Tectonics of the Southern Central Andes*. Springer Verlag, Berlin, Heidelberg.

Beekman A.N. (2008) - *A comparison of experimental ReMi measurements with various source, array and site conditions.* Master's thesis, University of Arkansas, USA.

Bertalot D. (2011) - *An overview on field and experimental evidences concerning seismic liquefaction induced settlement of buildings with shallow foundations*. Obras y Proyectos, 10, 36-45.

Carteau C. (2013) - *Caracterización de suelo en Villa Las Araucarias (Arauco) mediante refracción de microtremores (ReMi)*. Tesis para Optar el grado de Geofísico, Departamento de Geofísica, Universidad de Concepción, 128 pp.

Donoso C. (2011) - *Caracterización de Suelos en las localidades de Arauco, Colcura, San Pedro de la Paz y Concepción mediante Prospección Eléctrica*. Tesis para Optar al grado de Geofísico, Departamento de Geofísica, Universidad de Concepción, 153 pp.

Galli C. (1967) - *Geología urbana y suelo de fundación de Concepción y Talcahuano, Chile*. Departamento de Geología y Mineralogía, Instituto Central de Química. Universidad de Concepción. 248 pp.

Gonzales A. & Victoriano P. (2005) - *Aves de los humedales costeros de la zona de Concepción y alrededores*. In: Smith-Ramírez C., Armesto J.J. & Valdovinos C. (eds.) "Historia, biodiversidad y ecología de los bosques costeros de Chile". Santiago Editorial Universitaria, p. 485-497.

Ilabaca P. (1989) - *Evolución de la Costa de Concepción: El caso de las bahías de Concepción y San Vicente*. Revista de Biología Pesquera, 18, 29-35.

Isla I., Quezada J., Martínez C., Fernández A. & Jaque E. (2012) - *Maximum Holocene highstand for the coastal plains of the Arauco Gulf, Biobío Region: A sea-level curve for Chile*. Journal of Costal Research, 28, 1, 102-111.

Kaizuka S., Matsuda T., Nogami M. & Yonekura N. (1973) - *Quaternary tectonic and recent seismic cristal movements in the Arauco peninsula and its environs, central Chile*, Geographical Reports Tokio, Metropolitan Univiversity, 8, 1-49.

Kramer S.L. (1996) - *Geotechnical Earthquake Engineering.* University of Washington, Prentice Hall, 653 pp.

Lira E. (2009) - *Problema de n1 capas y un semiespacio: Filtro de Gosh*. Facultad de Ciencias Físicas y Matemáticas, U de Chile, 1-7.

Louie J.N. (2001) - *Faster, better: Shear-wave velocity to 100 meters depth from refraction microtremors arrays*. Bullettin Seismological Society of America, 91, 347-364.

Mardones M. (2005) - *La Cordillera de la Costa: Caracterización Físico-Ambiental y Regiones Morfoestructurales*. In: Smith-Ramírez C., Armesto J.J. & Valdovinos C. (eds.) "Historia, biodiversidad y ecología de los bosques costeros de Chile". Santiago Editorial Universitaria, 39-59.

Mardones M. & Jaque E. (1998) - *Geomorfología del Valle del Río Laja*. Primer Congreso de Ciencias de la Tierra, 115-121.

NCh433 of. 96 (1996) - Norma *Chilena Oficial "Diseño Sísmico de Edificios"*. División de Normas del Instituto de Nacional de Normalización (INN). Decreto No. 172 del 05 de Diciembre de 1996 del Ministerio de Vivienda y Urbanismo.

Obando T. (2009) - *Modelación geomecánica y temporal de la licuefacción en suelos de minas no metálicas. Estudio Caso: Ciudad de Managua*

(Nicaragua). Tesis Doctoral, Ed. Universidad Internacional de Andalucía UNIA (Huelva, España), Huelva, 900 pp.

Quezada J., Jaque E., Belmonte A., Fernández A., Vásquez D. & Martínez C. (2010) - *Movimientos co-sísmicos verticales y cambios geomorfológicos generados durante el terremoto Mw=8.8 del 27 de Febrero de 2010 en el centro-sur de Chile*. Revista Geográfica del Sur, 2, 11-44.

Verdugo R., Villalobos F., Yasuda S., Konagai K., Sugano T., Okamura M., Tobita T. & Torres A. (2010) - *Description and Analysis of Geotechnical Aspects Associated to the Large 2010 Chile Earthquake*. Obras y Proyectos, 8, 25-36.

Wathelet M. (2005) - *Array recordings of ambient vibrations: Surface-wave inversión*. PhD thesis, Université de Liège, Bélgium.

Wathelet M. (2008) - *An improved neighborhood algorithm: Parameter conditions and dynamic scaling*. Geophysical Research Letters, 35, L09301.

Youd T. L. & Hoose S.N. (1977) - *Liquefaction susceptibility and geologic setting*. In Proceedings, 6th World Conference on Earthquake Engineering, New Delhi, India, 2189-2194.

Youd T.L. (1984b) - *Geologic Effects – Liquefaction and Associated Ground Failure*. In Proceedings of the Geologic and Hydrologic Hazards Training Program, Open – File Report 84-760, U.S. Geological Survey, Menlo Park, California.

Appendix 1

GEOELECTRICAL APPLICATION

Geoelectrical prospecting allows to exploring resistivity from sub-surface in a broad range. Resistivity values [Ohm-meter] can vary up to 15 orders of magnitude. Conduction is defined as electrolytic type in sense that water presence into rocks porosity allows electrolytic conduction. In present work resistivity values ranged around 10^0 and 10^3 [Ohm-m].

Vertical Electrical Sounding [VES] - also known as Schlumberger Sounding- and Dipole-Dipole profile were conducted on field. Measurements were carried out using a transmitter with power up to 400 Volts to generate currents of about 200 mA [milli-Amperes]. Profiles distances AB extended up to 60 meters for dipole-dipole and 100 meters for VES. Spacing between electrodes was adjusted to 2 meters. Distance between voltage difference electrodes in VES was adjusted to 0.5 meters.

VES data set was processed using IPI2DINV and IPI-2WIN together a *matlab* routine (Lira, 2009). Dipole-dipole data set were processed using RES2DINV. Inversion models were adjusted with an error up to 20%. Details can be found in Donoso (2011).

ReMi-SEISMIC REFRACTION APPLICATION

Measurements were carried out with a GEODE (Geometrics) seismograph by using 17 and 23 vertical geophones which natural frequencies are respectively 4.5 and 14 Hz for ReMi and seismic refraction-. Seismic refraction source was simulated by hitting a metal base with an 8-kilogramms hammer. Sampling gap was fixed to 0.25 millisec. (ms) and registering time to 0.25 – 0.5 sec. For ReMi method sampling gap was fixed to 2 ms for registering times of 30-32 sec. Measurements were repeated twice. Profiles lengths reached up between 64 and 80 meters with spacing among geophones of 4 m.

Data processing was done by using a pair of routines developed in frame of Carteau thesis work (2012) together the use of GEOPSY software. These routines were tested with matlab routines provided generously by A. Beekman (Beekman, 2008). Main difference between Beekman's routines and the one developed by Carteau (2012) is the way for calculating slant-stack transform. Inversion process from dispersion curve to S-wave vertical velocity accepts different possible solutions, so it is relevant to count with previous geological information as initial model. In this work such process is carried out using a free-distributed software (Dinver) created by Marc Wathelet (Wathelet, 2005; Wathelet, 2008). Here the so-called Neighbourhood algorithm is implemented. Details related with theory and data processing for ReMi method are exposed in Carteau (2012).

The spectral analysis required for ReMi analysis is based mainly in Louie (2011) which establish as control parameter the spectral ratio R(p,f).

$$R(p_l, f) = S_A(p_l, f)\frac{n_p}{\sum_{l=0}^{np-1} S(p_l, f)}$$

n_p is the number of steps for p discretization.
$S_A(p_l, f)$ is the potency spectra.

$R(p_l, f$ is the ratio between the potency spectra of one or several registers for a particular (selected) value of slowness and frequency and the average of potency spectra along slowness in such selected frequency.

V_{S30} PARAMETER

Before 2010 Maule Earthquake Seismic Chilean Norm NCh433 Of96 used to classify soils into 4 categories from high to low quality. Here geotechnical and geophysical parameters are combined to establish such classification. One of these parameters has been often the P-wave velocity (Vp). On November 2th, 2011 a relevant change was established by Chilean government. It became obligation to know - apart of Vp – the S-wave propagation velocity average for the first 30 meters depth. This parameter is known as V_{S30}. V_{S30} is calculated according to equation (A1) where Z_i is the i_{th} layer potency.

$$V_{S30} = \frac{30}{\sum_{i=1}^{n}\frac{Z_i}{V_{Si}}}$$

(A1)

This new classification establishes the following categorizing (tab. 1) for the so-called V_{S30} parameter.

Theory and observations indicate that soils behavior against strong motion is clearly better in rock outcrop than finer and softer soils. F-type soils are those showing singularities in their mechanical behavior and it is requirement a geotechnical study: sands, mud, organic soils among others.

(ms received 30 September 2014; accepted 30 April 2015)