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SEISMIC ZONATION OF THE SANTIAGO BASIN, CHILE

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ABSTRACT

The shaking of the ground during an earthquake depends upon many factors, such as: the characteristics of the source, the path followed by the seismic rays, and the local conditions at the observation site. In the present study, we focus on the local soil conditions at the Santiago Basin, aiming to obtain a seismic classification of the existing deposits. We consider several parameters, such as superficial geology, dynamic properties of the soils, and the distribution of damaged observed during the last great earthquake that occurred in the coasts adjacent to the Santiago Basin (3/03/1985). From this analysis, we obtain a map where two zones can be recognized; each one with a homogeneous expected seismic hazard.

Keywords: seismic zonation, Santiago Basin, superficial geology, microtremors, seismic intensity

INTRODUCTION

The response of structures during a large earthquake has shown the strong influence of the local site conditions, phenomenon known for almost 200 year when became evident from the different behavior of localities near the Mississippi and Ohio river compared to up-hill, during the 1811-1812 New Madrid seismic sequence (Drake, 1815). Similar cases of the strong influence of site effect were detected during Japan 1891 great earthquake (Milne, 1898), San Francisco 1906 earthquake (Wood, 1906), and Long Beach 1933 earthquake (Wood, 1933). The city of Santiago is not an exception to this behavior, as shown during the Valparaíso 1906 earthquake (Montessus de Ballore, 1916) and 1985 earthquake (Monge, 1986). During this last event, Astroza and Monge (1989) reported a difference between 0.5 and 2.0 in intensity within close regions (see, also Menéndez, 1991). Astroza and Monge (1991) showed that the largest amplifications were produced in fine-grained and fluvial deposits, with low grade of consolidation.

In this study, we identified areas within the Santiago Basin where the seismic demands are higher; hence, more probable to suffer damage during an earthquake due to local conditions. We collected information from several sources, ranging from mostly descriptive data (such as superficial geology) to quantitative data (such as geotechnical and geophysical). From the geological information we conclude that the Santiago Basin has four main units, each one with particular properties that defines its seismic behavior: clays and fine-grained sediments from the Northeast, volcanic ashes, Mapocho and Maipo gravels, and alluvial fans. Considering the criteria presented in the seismic design codes of building and industrial installations, we group these units into two classes with homogenous seismic demand.

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GEOLOGY

Santiago Basin is an irregular depression with variable depths ranging from few hundreds meters up to 500 m (Araneda et al., 2000). In order to properly define the sedimentary deposits within the Basin, we considered the main granulometric characteristics in the first 30 m, practically eliminating the transition zones between different units. We use information from wells, and studies by Valenzuela (1978), Wall et al. (1999), Milovic (2000), Fernández (2001, 2003), Rauld (2002), Sellés and Gana (2001), and Fock (2005).

Considering the information mentioned before, we defined the following units (shown in Figure 1):

- *Unit I.* Bedrock. It outcrops in mountain chains around the Santiago basin and isolated hills (Chena, Santa Lucia, Renca, and others). According to Fock (2005), toward the NE and E outcrops are mainly rocks of Abanico Formation, intruded by igneous rocks. The N and W is dominated by older rocks, assigned to Lo Valle, Veta Negra, and Lo Prado formations and Cretaceous intrusive bodies.
- *Unit II*. Gravel. Coarse-grained sediments, dominantly sandy gravels of medium to high density mainly compose this unit. In the Santiago Basin, mainly young deposits of Maipo, Mapocho, and Clarillo rivers compose them.
- *Unit IIIa.* Matrix supported deposits of blocks and subangular gravel in sandy-clayey matrix, interleaved by sand, silt, and clay. In the area of study, they correspond to small alluvial fans located at the slope toe of the main hills that surround the Santiago Basin.
- *Unit IIIb*. Deposits of gravels and blocks in sandy-clayey matrix, assigned to old alluvial fans related to Mapocho river, in the northeaster part of the basin. They form a medium height relief such as Apoquindo and Calan hills.
- *Unit IV*. Matrix supported gravels and blocks in a clayey-sandy matrix. They correspond to old landslide deposits in the northeastern and eastern parts of the basin.
- *Unit Va*. Gravel deposits in clayey-sandy matrix with abundant interbeds of sand, silt, and clay as well as of thick clayey silt soils. They correspond to alluvial fan deposits of Colina and Arrayán creeks.
- *Unit Vb.* Deposits of fine to coarse-grained sand mixed with variable amounts of silt and clay, assigned to deposits of Lampa creek.
- *Unit VI.* Deposits of over 20 m thick of volcanic ash with litics and pumice, assigned to the unit called Pudahuel Ignimbrite, with sand, silt, and gravel interbeds. The deposits form a smooth hilly relief in the western and northwestern areas of the Santiago basin.
- *Unit VII.* Deposits of silt and clay with gravel, sand, and ash interbeds, mainly located in the northern area of the Santiago basin.
- *Unit VIII.* Recent fluvial deposits of variable granulometry, from gravel to silt.

The contacts between some interlocked units were determined taking into account the seismic intensity and fundamental periods, along with detailed review of stratigraphic cross sections to establish the dominant unit. An example of this are the deposits located between the Renca and San Cristobal hills.

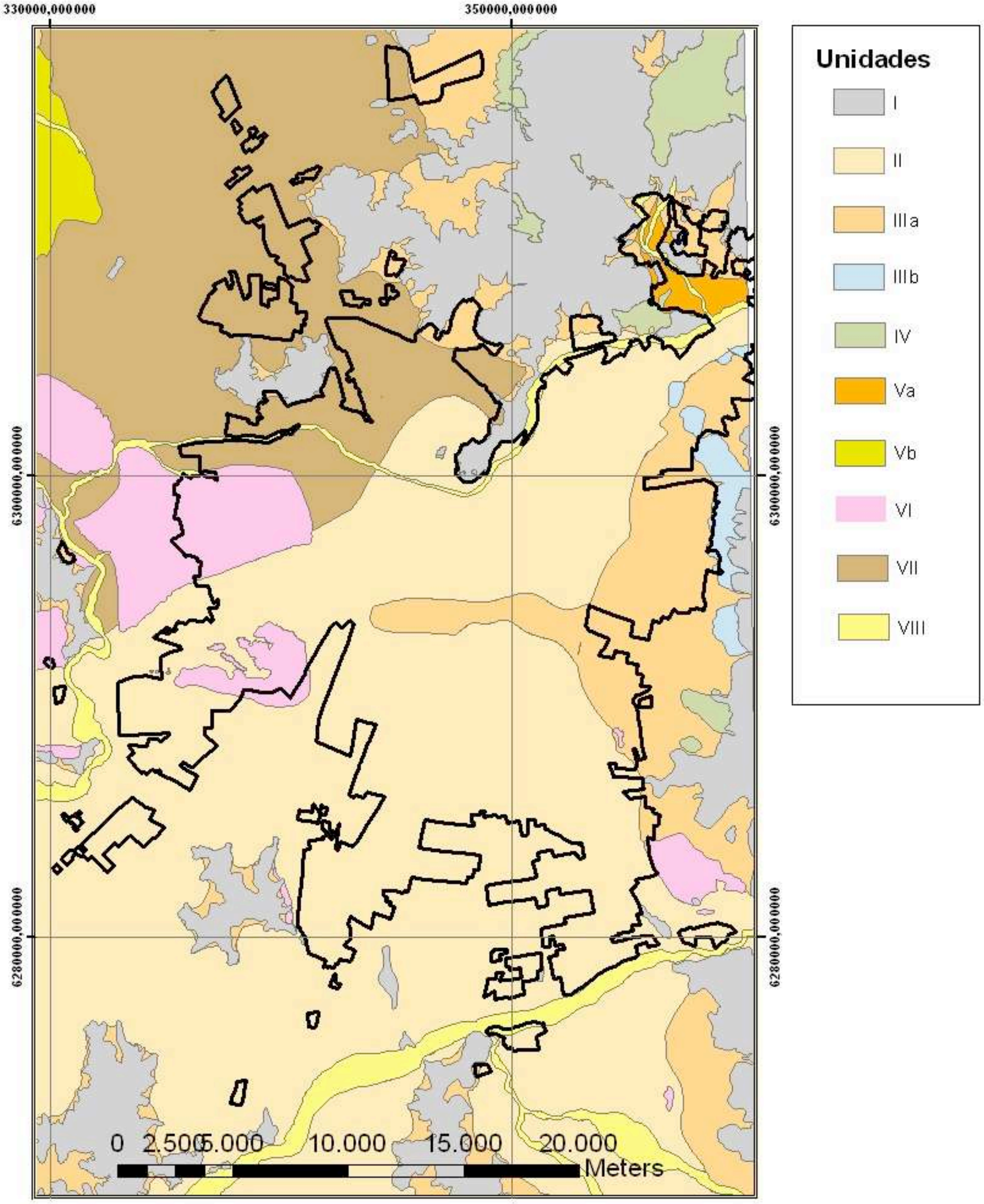

Figure 1. Map with the superficial geology of the Santiago Basin, see label on the side. The black line represents the urban limit.

DYNAMIC PROPERTIES OF SANTIAGO BASIN'S DEPOSITS

Considering the fact that seismic design codes classify different sites based on the dynamic properties of the soils, we believe that any microzonation study should include the fundamental vibration period of soils and the shear wave propagation velocity. The Santiago Basin has hosted several studies relative to its seismic response, such as microtremors (Pasten, 2007; Bonnefoy-Claudet et l., 2008; Pilz et al., 2009) and seismic refraction (Ponce, 1998; Geo-E Tech, 2007); Figure 2 right shows all the data used in this study.

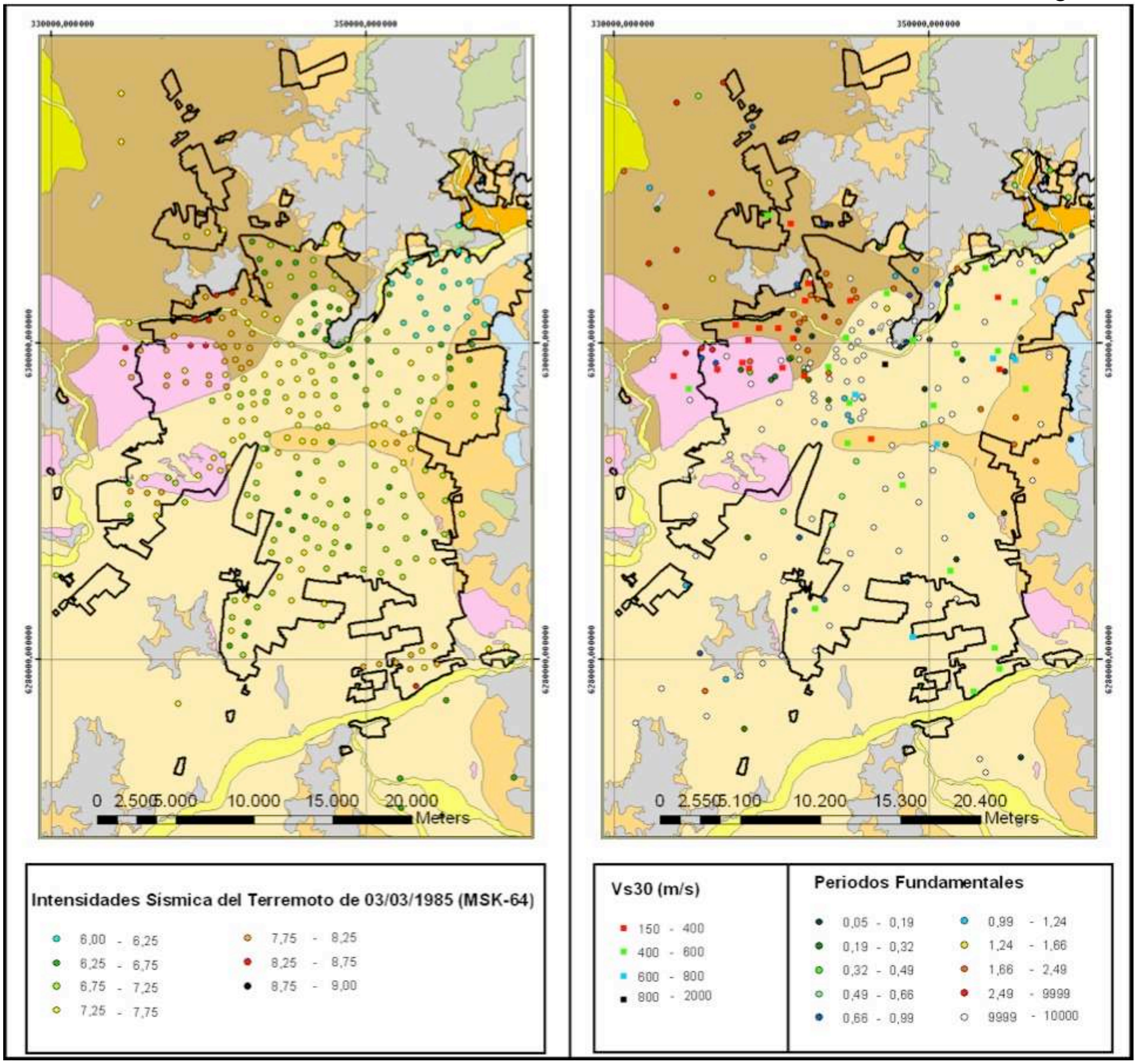

Figure 2. Maps with the superficial geology (see label in Figure 1) with the seismic intensities for the 3/03/85 earthquake (left) and Vs30 and fundamental period of the soils (right).

Fundamental Vibration Period

Nakamura (1989, 2000) popularized the used of the spectral ratio of the horizontal over the vertical component (H/V) from microtremors as an effective and economic tool to estimate the fundamental vibration period of the soils. In this study, we used the data collected by Pasten (2007), consisting in 264 measurements; some of them have been eliminated due to the strong influence of transients (Bonnefoy-Claudet et al., 2008), leaving the ones presented in Figure 2, right.

From the analysis of the microtremors, we distinguish four kinds of H/V curves, as shown in Figure 3: (a) flat curve, with no clear peak, (b) high amplitude at low frequencies, being the rest flat, (c) peak at low frequencies, with other peaks at higher frequencies with low amplitude, and (d) high amplitude peak at higher frequencies.

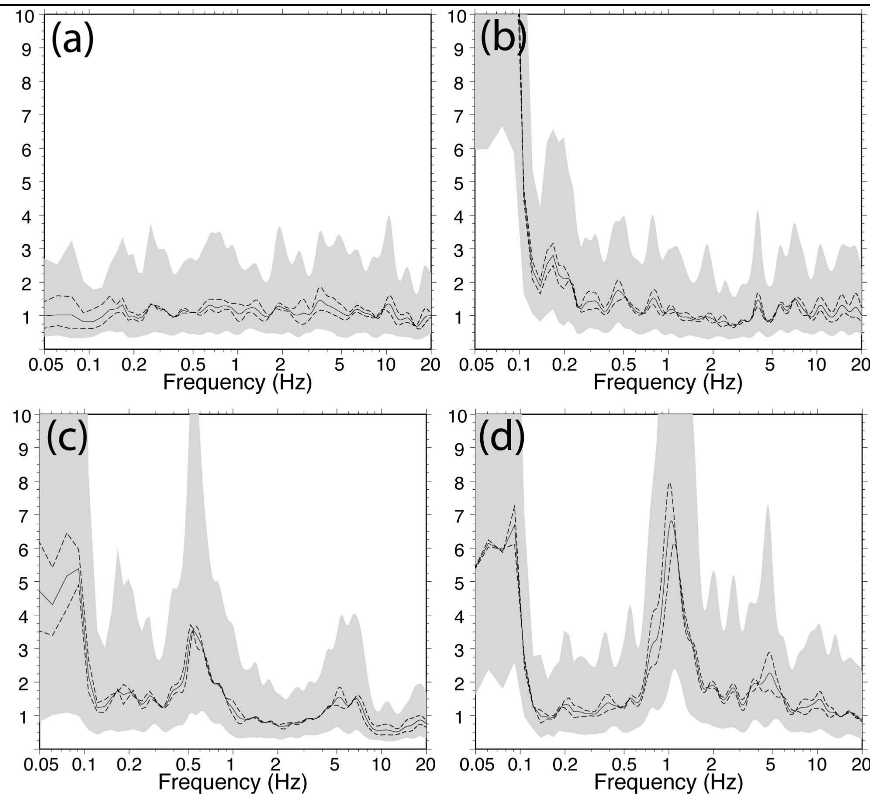

Figure 3. Taxonomy of the H/V spectral ratio responses observed at the Santiago Basin; dashed lines represent the ratio for each horizontal component, while in continuous lines is shown the average and the gray area represents the standard deviation. The graphs comes from: (a) and (b) Unit II, (c) Unit VII, and (d) Unit IIIa.

Ruiz and Leyton (2010) performed several tests on the instruments used in the microtremors measurements and concluded that the low frequency peaks correspond to electronic noise; therefore, they should be eliminated from the analysis. Hence, the H/V curves type (b) become type (a) and curves with forms such as the ones presented in (c) and (d) are classified as showing a clear peak, but with variations in its amplitude. In this work, we classified these two kinds of curves in the same way, ignoring the influence of the peaks amplitude, which Bonnefoy-Claudet et al. (2006) have shown to be related to the impedance between the rock and the sediments.

The analysis of microtremors measurements we are able to estimate the fundamental vibration period, in cases where a strong impedance contrast exists between the rock and the sedimentary deposit (Bonnefoy-Claudet et al., 2006). In the Santiago Basin we were not able to identify a characteristic fundamental period in those sites located over gravel (Unit II), probably due to the high rigidity of these deposits, resulting in a low impedance contrast with the basement. The remaining fundamental periods present a large range, from 0.05 up to 2 sec. According to this parameter, the geological units from Figure 1 can be grouped into the ranges shown in Table 1.

Table 1. Fundamental period for some superficial geological unit.

Geologic Unit (see Figure 1)	Fundamental period, sec
IIIa, VI, VII	≥ 0.5
II, Va	< 0.5

Shear wave propagation velocity

We determined the shear wave velocity in several sites (Figure 2), being the strongest limitation the fact that most of the measurements didn't go below the upper 20 m (Ponce, 1998; Geo-E Tech, 2007). From this information, we estimated the average shear wave propagation velocity (Vs30, IBC, 2007) assuming that that the lower most layers extend beyond; this assumption is conservative, considering that, in most cases, the shear wave velocity increases with depth. Given these values, we group the geological units into the ranges presented in Table 2. From this Table we can see that the sedimentary deposits in the Santiago Basin can be considered as rock or hard soil, according to IBC (2007), or Type II and III, according to NCh433 (INN, 1996).

Table 2. Shear wave velocity Vs30[*] for some superficial geological unit.

Geologic Unit (see Figure 1)	Vs30[*], m/sec
IIIa, VI, VII	150 – 400
II	400 – 800

DISTRIBUTION OF DAMAGE FOR THE 3/03/85 EARTHQUAKE

The detailed analysis of the distribution of damage produce by large earthquakes has enabled the identification of an increase of destructiveness in certain areas within a city, mainly due to local conditions. These effects have been observed for the several great earthquakes: 1906 (Ms=8.2), 1965 (Ms=7.1), 1971 (Ms=7.5), and 1985 (Ms=7.8). Indeed, the 3/03/85 earthquake left a clear signature of the damage in the surveys, for reparation issues, elaborated for all the municipalities. Following Monge and Astroza (1989), we processed of this information and estimated the seismic intensities in 21 municipalities of the Santiago Metropolitan area and several localities in the region, as shown in Figure 2. This earthquake had an epicenter in front of Valparaíso and corresponds to the repetition of the large earthquakes in this region, with an estimated period of 82 ± 6 years (Kausel, 1986), which mainly control the seismic demand of Santiago Metropolitan region.

Table 3 presents the range of values found in the geological units defined for the Santiago Basin; note that the intensities in Las Condes and Vitacura (grade 6.0 in MSK-64 scale) have not been considered due to a possible underestimation of this value produced by the fact that all the surveyed structures were classified as Class C of vulnerability. This value can increase at least ½ point, if we consider that, given the quality of the structures in these zones, they might correspond to Class D of the vulnerability scale (Gonzalez, 1998).

Table 3. Seismic intensity for some superficial geological unit.

Geologic Unit (see Figure 1)	Intensity for the 3/03/85 earthquake, MSK-64
VI, VII	7.0 – 8.5
IIIa	7.0 – 7.5
II	6.5 – 7.5

At Maipú, southwester of the ash deposits (Unit VI), we find a seismic intensity of 8.0 in an area located over Unit II, composed by gravels. We believe that this high intensity, exceeding the average value for this deposit, is due to the presences of ash interbeds. Nowadays, we do not have enough data to confirm

[*] We estimate these values to be lower limits due to the extrapolation performed, see details in text.
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this information; hence, we need further information of the upper 30 m in this area. In Puente Alto, we also observe high intensities in gravel deposits (Unit II); however, up to this date, we do not have enough data to improve the classification of this superficial geology in that area. Nevertheless, there are certain geological observations near the bridge that crosses the Maipo river going to Pirque, indicate the presence of thick lenses with ash matrix; even more, there are clear observations of Unit VI in the northeaster part of this area.

We believe that our current knowledge of superficial geology is not enough to completely explain the level and distribution of damages after a large earthquake (for example, within Unit II); therefore, further analysis are required to understand the variations observed inside one unit. We think that future investigations should be oriented to improve the characterization of the upper 30 m, along with a better model of the basement's depth.

Nevertheless, in general terms and as a first approximation, we can see a strong correlation between the intensities observed and the geological unit in the Santiago Basin, enabling us the determinations of limits for microzonation purposes, even to areas where we only have geological information.

SEISMIC ZONING

The seismic zonation of several cities has been made performed on an empirical method based on the observation of the damaged produced by a large earthquake and measurements of microtremors (Monge, 1990). These results has enabled the correlation of site effects not only with the superficial geology, but also with the underground water-level, shape of the basement, topography, and dynamic properties of the superficial sediments. In particular, for the Santiago Metropolitan area, Astroza and Monge (1991) and the MINVU (1989) report presented seismic zonation studies, mostly based on the observations of the intensities observed for the 3/03/85 Valparaíso earthquake (Menéndez, 1990) and the geology (Astroza et al., 1989). Astroza and Monge (1991) identified four zones with different intensity levels, being the municipalities of Cerro Navia, Quinta Normal, Lo Prado, Pudaheul, Maipú, and Puente Alto the ones with highest values. On the other hande, Midorikawa (1990) and Pérez (1988) concluded that was not possible to make a zonation of Santiago and Viña del Mar from studies of microtremors measurements, due to the peculiar characteristics of their soils.
Considering all the information collected these last years about the geology, the dynamical properties of the deposits, seismic intensities for the 3/03/85 earthquake, we propose a seismic zonation for the Santiago Basin, which includes the criteria used in seismic design codes. This zonation considers two areas, shown in Figure 4, with the geological units presented in Table 4. Nevertheless, we have to keep in mind the fact that certain areas have very scarce information, such as units IIIa, Va, and Vb, from Figure 1.

Table 4. Superficial geology per seismic zone.

Seismic Zone	Geologic Unit (see Figure 1)
A	II, Va
B	IIIa, Vb, VI, VII

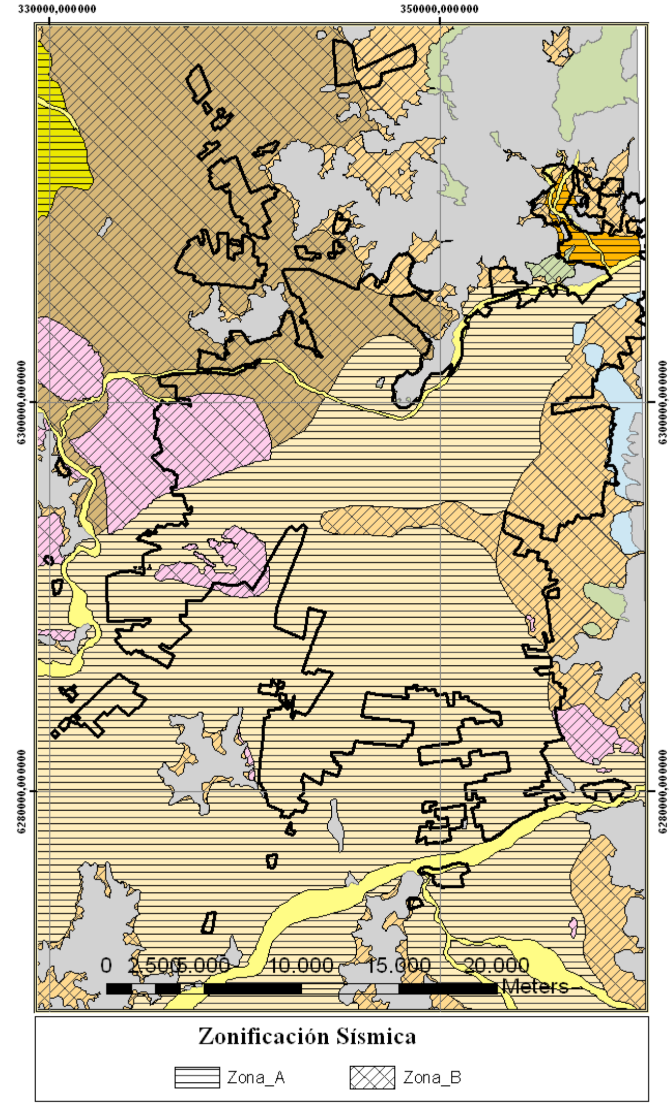

Figure 4. Map with the superficial geology (in colors, see Figure 1 for details) and the seismic zones defined in this study (lines).

CONCLUSIONS

The seismic zonation that we propose in this work considers: (i) the characteristics of the superficial geology, including the granulometric characteristics of the upper 30 m, (ii) the dynamic properties of the soils, quantified from the average shear wave propagation of the upper 30 m (Vs30) and the fundamental vibration period (as long as it can be estimated from microtremors measurements, such as H/V spectral ratio), and (iii) the amplification of the ground during a large earthquake estimated by seismic intensities evaluated from damage distribution. Recently, we have been working on the update of the damage due to a large earthquake at Santiago, considering the effects of the Maule 2010 events; our efforts have been focused on two areas: validate the information observed during the Valparaíso 1985 earthquake and extend the area of study into regions that were not populated during this last event.

At any rate, we believe that further studies should be performed in order to improve the characterization of the seismic response of certain geological units, which might suggest the use of a larger number of seismic zones within the Santiago Basin.

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