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DEFINITION OF SEISMIC RISK AREAS IN VIÑA DEL MAR (CHILE) FROM GEOTECHNICAL DATA ANALYSIS

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Abstract

The evaluation of the local ground conditions and the estimation of its influence in the seismic motion is the main objective of the seismic microzonation studies. The last earthquakes in the city of Viña del Mar showed a similar distribution of building damage that may be related to soil conditions and the height of the buildings. The municipality of Viña del Mar is developing a seismic microzoning, analyzing 440 geotechnical reports to define an area of risk to be used in the city planning. This has allowed to prepare a georeferenced database of the characteristic parameters of the soils and the V_S structures down to 30 m. The V_S models were obtained from Standard Penetration Tests (SPT) and some V_S data measured with Refraction Microtremor (ReMi) technique. These geotechnical data show that the areas of the hills are identified with rocks whereas the plain consist of sedimentary deposits of sand, silty sands with intercalations of clays, silts and gravels which reach more than 100 m deep. The V_S estimated from the NSPT data are very low ($V_S \leq 200$ m/s) in the upper 6 m, increasing in the range from 5 to 15 m, and generally exceeding 300 m/s for the deeper layers. The coast and the Marga-Marga river valley have $V_{S30} < 300$ m/s, while, in general, it is greater in the rest. Stratigraphic columns, maps of the lithological units and representations of V_{S10} and V_{S30} values have been made to classify the soils according to the NCh433 norm and to define the area of greatest seismic risk. The results obtained confirm that soil conditions had a clear influence on the spatial distribution of the macrosismic intensity in large historical earthquakes.

Keywords: Viña del Mar; local conditions; geotechnical and seismological characteristics.

1. Introduction

Viña del Mar is located on the central part of the Pacific Ocean coast of Chile, being part of the metropolitan area of Valparaíso. The city, which extends near the mouth of the Marga-Marga river (estuary) towards the Pacific Ocean, has been repeatedly damaged by major historical and recent earthquakes, especially those of 1906 (Mw 8.2), 1960 (Mw of 9.5), 1985 (Mw 8.0) and 2010 (Mw 8.8).

Viña del Mar, located at the northern end of the rupture area of the gigantic earthquake occurred in Chile in 2010 (Mw 8.8, Imax = IX-EMS) [1], is mainly built on a plain of marine and alluvial sedimentary deposits, mainly consisting of sands and gravels and silty sands, with some anthropic fillings on top.

The damages observed in the buildings of Viña del Mar after the 2010 earthquake were very similar to those occurred in the 1985 earthquake and show a direct relationship between the soil conditions and the building heights.

Therefore, Viña del Mar is in one of the most active seismic areas in Chile. Leyton et al. [2] estimated a maximum expected acceleration higher than 0.7 g for a return period of 475 years, whereas it is 0.6 g according to the GSHAP project [3]. On the other hand, the Chilean seismic design code [4] provides for an effective seismic acceleration of 0.4 g.

Since it is well known that ground conditions modify the seismic response of the soil, giving rise to seismic motions of different intensity and frequency content, it was decided to organize and analyze the data of soil surveys and mechanics to map the geotechnical characteristics and the shallow V_S structure in the urban area.

To meet this goal, a seismic microzonation study is being developed for the Municipality of Viña del Mar, through the analysis of 440 geotechnical reports to define a risk area for the new Community Regulatory Plan. This has allowed to plot the characteristic parameters of the soils and the shallow V_S structure down to 30 m in 93 of these sites. The V_S models were estimated from SPT data and from direct V_S measurements at some points with ReMi technique.

2. Methodology: compilation, parameterization and analysis of geotechnical data.

The "Plan of Viña" is so named for being a very flat area of the city (generally between 6 and 10 m of height and with a length of more than 3 km) slightly inclined towards the west. From the geomorphological point of view, it is a triangular shaped alluvial terrace of fluvial-marine sedimentation with coastal batholith (of Paleozoic age).

A first classification of the city's soils (centered on the seismic response) considers three types: intrusive rocks, consolidated sediments and unconsolidated sediments. These sedimentary deposits reach up to 100-130 m thick [5, 6, 7, 8] and the water table is at about 4 m of depth in average. Viña del Mar has several areas of soft or poorly consolidated soils, which creates a great risk for people in case of earthquake.

Currently, the Urban Planning Regulations of Viña del Mar Municipality is being modified. For the first time in Chile, a seismic microzonation is being incorporated, with a detailed risk study to define areas restricted to urban development according to Article 2.1.17 of the general ordinance of urban planning and construction [9]. The technical team of the Urban Advisory Department of the Municipality of Viña del Mar is carrying out an urban regulation in conjunction with technical agencies and specialists to define risk areas or restricted areas based on this seismic microzoning study, which includes the classification of the shallow ground structure.

The purpose of this seismic microzoning is to evaluate the local soil response (and other potential effects) to minimize earthquake damage in buildings, facilities and especially to humans. The microzonation seeks to obtain the response of the soil to the seismic excitation and consequently, the variation of the characteristics of the seismic motion on the surface. This process consists of dividing the entire area into smaller areas considering the characteristics of the seismic shaking and the induced hazards (for example, surface fractures, liquefaction, landslides, settlements, etc.), identifying and delimiting zones that have the same seismic response.

Seismic microzoning is being carried out with the analysis of 440 surveys and geotechnical studies (Figure 1), provided by the Municipal Works Department (DOM).

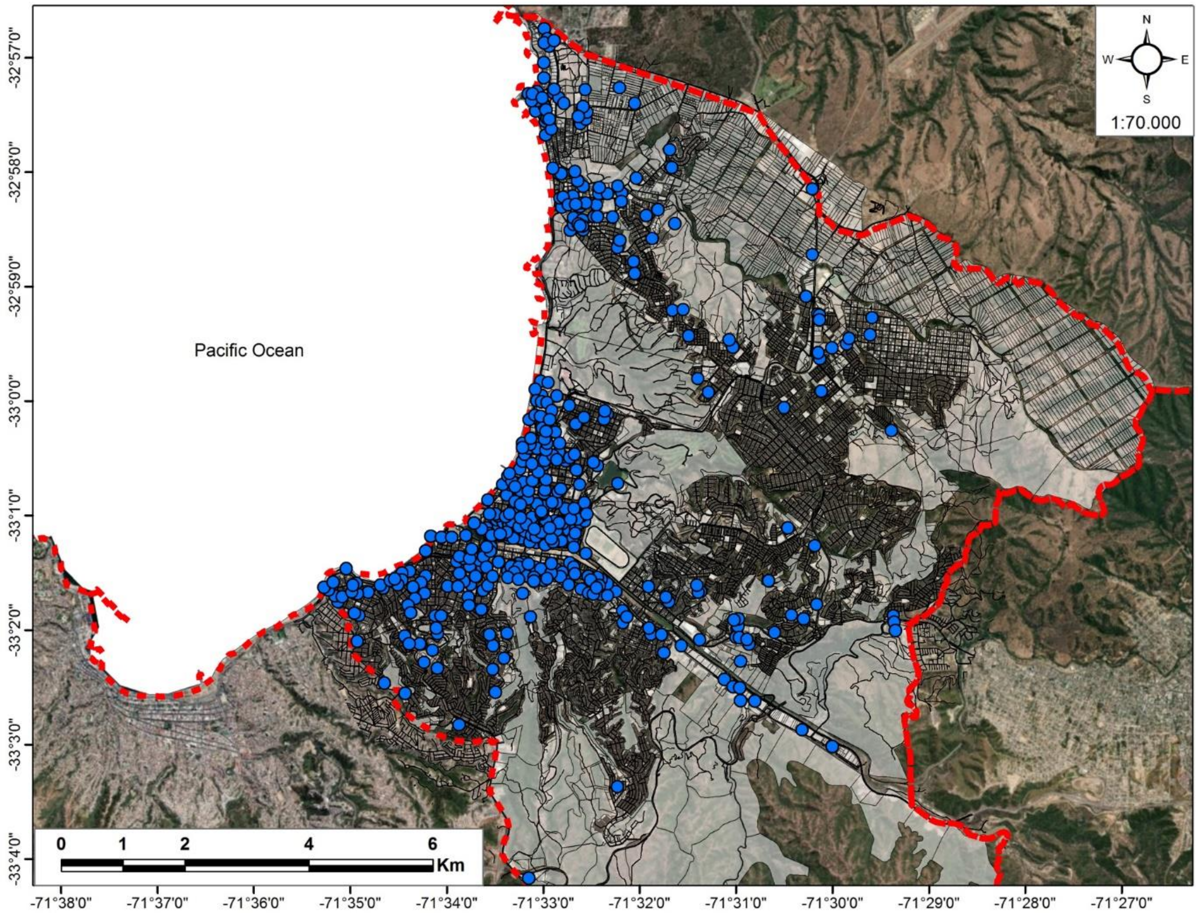

Fig. 1 – Mechanical surveys and geotechnical reports analyzed and georeferenced in GIS (dashed red line for communal boundaries).

As a framework to classify the soils of Viña del Mar we will use the Chilean Seismic Code Nch433 [4], where they are classified into 6 types, from type A, the consolidated-cemented soil or rock with Vs ≥900 m/s, to type E, soft soil of compactness or medium resistance with Vs <180 m/s. The Chilean Ministry of Housing (MINVU) exempts small buildings of less than 500 m² with a maximum of two levels (equivalent to approximately 8 meters in height) from performing shear wave tests (Vs) as long as it is not in the presence of special type F soils, (liquefiable, collapsible, etc., Decree No. 61 [10]). For this reason, the search for information in the Municipal Works Directorate (DOM) consisted of the review of more than 8.000 building folders that met the following characteristics: having three or more floors, one or more basement levels and a construction year later than the first version of the Nch433 norm (1971).

3. Geotechnical and Geophysical Parameters

The database was configured with a total of 440 points; 320 reports of Soil Mechanics of the DOM, 102 NSPTs taken from Carrasco, O. & Núñez, C. [11] and 8 studies conducted by Wood, S., Wight, J. & Moehle, J. [12]. The main parameters obtained were the general characteristics of the building, the lithological description, and soil parameters of both physical and mechanical types (NSPT, Granulometry, USCS Classification, Atterberg Limits, Internal Friction Angle, Cohesion, Poisson Module and Relative Density).

Once the information was parameterized, the data were tabulated in Excel format (see Table 1) and georeferenced in a geographic information system (ArcGIS of ESRI) every 0.5 m in depth, grouping the layers of similar lithological strata.

An example of a mechanical study with the information obtained from the geotechnical studies is shown in Table 1.

Table 1 – Geotechnical and geophysical parameters every 0.5 m.

Depth (m)		Lithology	USCS	Nspt	C	Φ°	Dr %	γt T/m³	LL	IP	μ
0.0	0.5	Poorly homogeneous filling of "dirty" gravelly-clayed-silty sand, of medium to fine sub-rounded grain, not cemented, with debris, remains of foundations, stone masonry walls, pieces of stones, bricks and rootlets; dark brown soil layer varying to blackish brown, of variable plasticity and with some cohesion down to 2.0 m; type "B" hardness	SC-SM					1.65			
0.5	1.0		SC-SM	*				1.65			
1.0	1.5		SC-SM	13				1.65			
1.5	2.0		SC-SM	13				1.65			
2.0	2.5		SC-SM	8				1.65			
2.5	3.0		SC-SM	8				1.65			
3.0	3.5	Natural sedimentary "blonde" fluvial sand, somewhat silty and with muddy slabs and little curly pebbles, without plasticity, medium to fine grain sub-rounded and dark yellow gray, without cementation or cohesion, not saline, containing in its upper2 / 3 erratic muddy slabs of about 20 cm thick; granular soil of high humidity and medium compactness increased to high compactness at the bottom of the stratum. Poorly graduated and crumbling soil in vertical cuts. Medium relative density soil stratum, with sub-strata of coarse to medium sand with fine gravel lenses, very prone to collapse in vertical cuts due to lack of cohesion; hardness to excavability estimated within the group and / or type "B"	SP-SM	38				1.80			
3.5	4.0		SP-SM	38				1.80			
4.0	4.5		SP-SM	19				1.80			
4.5	5.0		SP-SM	19				1.80			
5.0	5.5		SP-SM	19				1.80			
5.5	6.0	"Blonde" clean sedimentary sand, of natural fluvial estuary origin, inorganic, very silty, without plasticity, medium grain and light yellow or light gray color, with about 2% of quartz stones embedded and dispersed, with myceous flakes, without cementation or cohesion, non-saline and inorganic; homogeneous granular stratum saturated and of high compactness. Granular soil well graduated and crumbly in vertical cuts, very prone to collapse in vertical cuts due to lack of cohesion, hardness to excavability estimated within the group and / or type "C-FV".	SW	128	0	42	<80	2.09	0	0	0.2
6.0	6.5		SW	100	0	42	<80	2.09	0	0	0.2
6.5	7.0		SW	100	0	42	<80	2.09	0	0	0.2
7.0	7.5		SW	100	0	42	<80	2.09	0	0	0.2
7.5	8.0		SW	100	0	42	<80	2.09	0	0	0.2
8.0	8.5		SW	59	0	42	<80	2.09	0	0	0.2
8.5	9.0		SW	59	0	42	<80	2.09	0	0	0.2
9.0	9.5		SW	100	0	42	<80	2.09	0	0	0.2
9.5	10.0		SW	100	0	42	<80	2.09	0	0	0.2
10.0	10.5		SW	100	0	42	<80	2.09	0	0	0.2
10.5	11.0		SW	100	0	42	<80	2.09	0	0	0.2
11.0	11.5		SW	100	0	42	<80	2.09	0	0	0.2
11.5	12.0		SW	100	0	42	<80	2.09	0	0	0.2
12.0	12.5		SW	100	0	42	<80	2.09	0	0	0.2
12.5	13.0		SW	100	0	42	<80	2.09	0	0	0.2
13.0	13.5		SW	100	0	42	<80	2.09	0	0	0.2
13.5	14.0		SW	100	0	42	<80	2.09	0	0	0.2
14.0	14.5		SW	100	0	42	<80	2.09	0	0	0.2
14.5	15.0		SW	100	0	42	<80	2.09	0	0	0.2
15.0	15.5		SW	100	0	42	<80	2.09	0	0	0.2
15.5	16.0		SW	100	0	42	<80	2.09	0	0	0.2
16.0	16.5	Natural fluvial sedimentary sand; clean, non-stony, inorganic, non-silty, without plasticity, with medium-rounded and leaden-colored grain, with myceous flakes, without cohesion, with non-saline and inorganic cementation; homogeneous granular stratum, saturated and of very high compactness, practically impenetrable to probing. Very prone to collapse in vertical cuts due to lack of cohesion, with estimated hardness to excavability within the group and / or type C-IV	SP	100			<80	2.27			
16.5	17.0		SP	100			<80	2.27			
17.0	17.5		SP	100			<80	2.27			
17.5	18.0		SP	100			<80	2.27			
18.0	18.5		SP	100			<80	2.27			
18.5	19.0		SP	100			<80	2.27			
19.0	19.5		SP	100			<80	2.27			
19.5	20.0		SP	100			<80	2.27			
20.0	20.5		SP	100			<80	2.27			
20.5	21.0		SP	100			<80	2.27			

USCS: Unified Soil Classification System; Nspt: Standard Penetration Test; C: Effective cohesion; Φ ° S: Internal Friction Angle; Dr %: Relative Density; γt t/m³: Specific Weight; LL: Liquid Limit; IP: Plasticity Index; μ: Poisson Module.

The detailed determination of the stratigraphic-geotechnical model allowed to determine 338 stratigraphic columns, for which, the characteristics of the surface geological structure are shown down to the depths contributed by each soil mechanics study. As an example, the probe ID123, which reaches a depth of 35 m, is shown (Figure 2). These stratigraphic columns provide quite complete geotechnical information down to 20 m deep (and in many cases down to > 30 m) on the existing types of soil under the anthropic landfill, plant and/or edaphic soil.

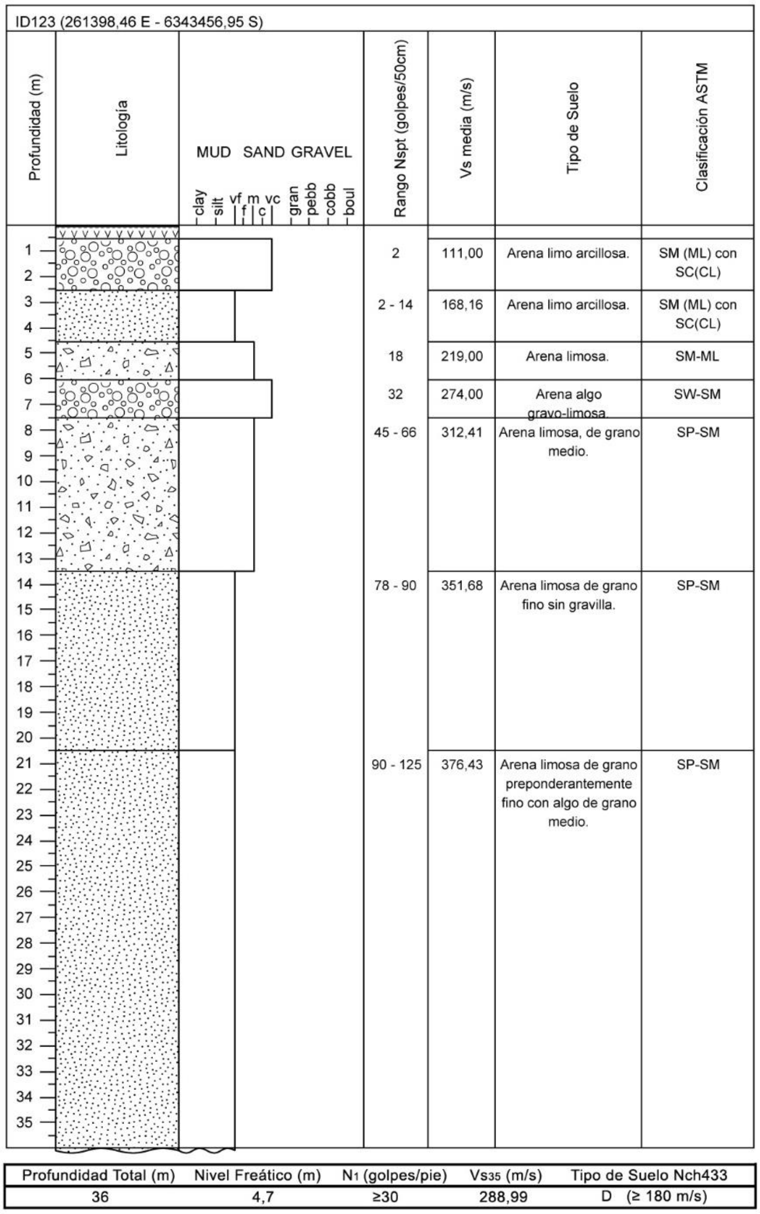

Fig. 2 – Stratigraphic column showing, every 0.5 m of survey, the lithology, size of grain, the range of NSPT as well as the average Vs per stratum, the lithological description of the soil and the USCS classification according to ASTM D2487. In addition, at the bottom of the Stratigraphic Column, a summary table is shown with the total depth of ground exploration, depth of the water table, N1, Vs_{35} and Type of soil (from Nch433 norm).

The stratigraphic columns obtained from the surveys, in each geotechnical report, as well as the identification tests (for example, granulometry by sieving, liquid limit and plastic limit) have been used to establish the type of soil according to the USCS (2010). In addition, SPTs have been used to characterize and delimit mainly four types of soil (Figure 3) in which the variations of the parameters in the upper 10 m have been taken into account, always omitting the thickness of anthropic landfill, topsoil and/or edaphic soil which, together with the thickness of low bearing capacity soils, constitute the minimum foundation depth, regardless of the building project. This provides valuable information on the very shallow ground conditions. To obtain the map of ground thicknesses, the values obtained in the surveys have been interpolated with the Inverse Distance Weighting (IDW) method using a GIS.

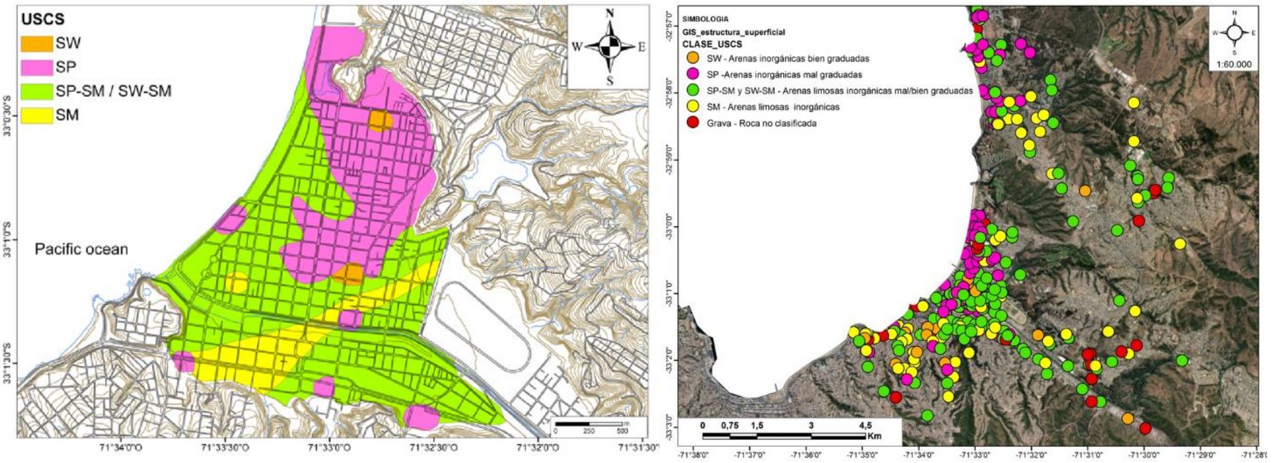

Fig. 3 – Distribution of the most abundant soil types in the upper 10 m according to USCS (2010).

In the Commune of Viña del Mar, the soils have important variations depending on the location of the surveys, as shown in Figure 3 (right). The area affected by the City Plan is described below (Figure 3-left), because it is the area with the highest population density, high-rise buildings and very poorly consolidated soils.

The well-graded inorganic sands (SW class), are the scarcest and are located in the N and center - E sectors. This alluvial deposit is made up of clean feldspar-sub-rounded quartz sands of medium to coarse grain and grayish-yellow color. Locally, they are called coarse blonde sand.

The second most profuse soil type, after the silty sands, is the poorly graded inorganic sands (SP type). It appears mainly on the N-NE and Center sectors. In addition, some scraps with these materials have been detected at the S and W edge. This type is made up of medium to fine sands of yellow, dark yellow or opaque gray-yellow with some fine gravel of medium to high compactness, increasing with depth.

The most abundant soil type corresponds to poor / well graded inorganic silty sands (SP - SM / SW - SM), located in the W, center, S and SE sectors. It is represented by a mixture of clean sands of estuary, poorly or well graduated, of medium grain and medium compactness, with yellow, dark yellow and grayish yellow colors, with some silts arranged in bags or lenses.

Finally, inorganic silty sands (SM) are presented in a strip with NE-SW direction in the SE sector. This soil is constituted by a sand with abundance of silty fines with greenish-yellowish and yellowish colors. The Atterberg limits and the plasticity abacus classify the silt as of low / medium compressibility.

4. Water table depth distribution

The depth of the water table obtained from mechanical rotational surveys with continuous sampling varies throughout the commune between 0.8 and 8.5 m (Figure 4 Right), with an average of 4 m and standard deviation of 1 m. It is appreciated that, in the area of the City Plan, it has a maximum depth of 6 m except for some specific points with greater depth at which it can reach 8.5 m.

The most dangerous area is the mouth of the Marga-Marga estuary (Figure 4 Left), because it has a very shallow water table that varies between 1 and 2 m deep. This condition, together with the type of soil, represents an important risk factor in case of earthquake.

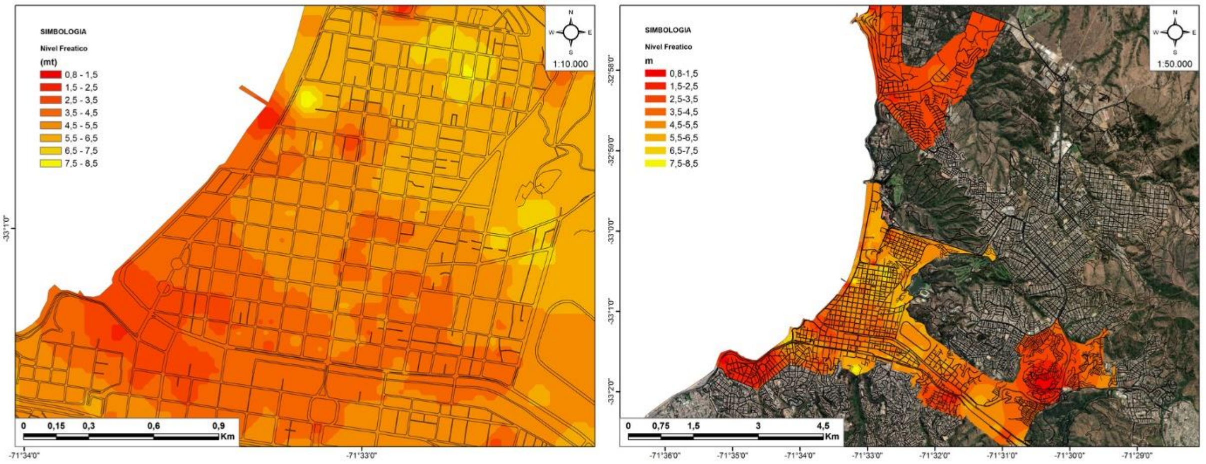

Fig. 4 – Distribution of water table depth values in the City Plan area (left), and throughout the Commune of Viña del Mar (right), obtained from 251 geotechnical reports.

5. Minimum Foundation Depth

The minimum foundation depth is that where the vegetable and / or edaphic cover is removed, as well as the anthropic filling (Figure 5 left) if detected. In addition, we must take into account the thickness of very low bearing capacity (sludge, Figure 5 right) on which it is not recommended to have any type of foundation as they present an irregular distribution and low degree of compaction. The sum of the thicknesses of all the represented soils of these types can be considered the minimum foundation depth; to this we must add the characteristics of each building project, such as lowering loads, number of plants below ground and type of structure.

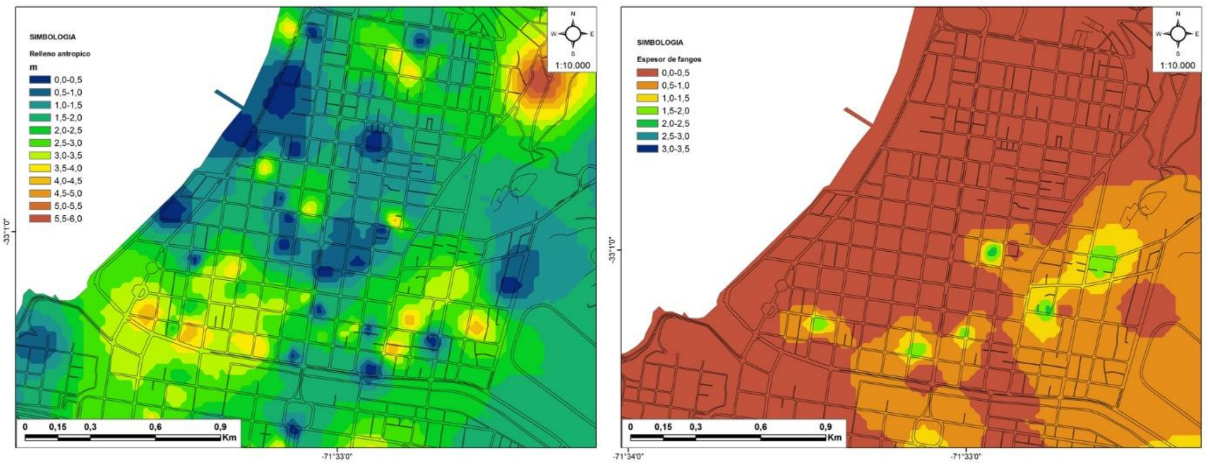

Fig. 5 – Anthropic fillings (left) and sludge (right) thickness maps.

This depth varies between 0.5 and 6.5 m (Figure 6 left), with the area near the estuary and the trace of the Marga Marga fault [8] having the highest values of foundation depth.

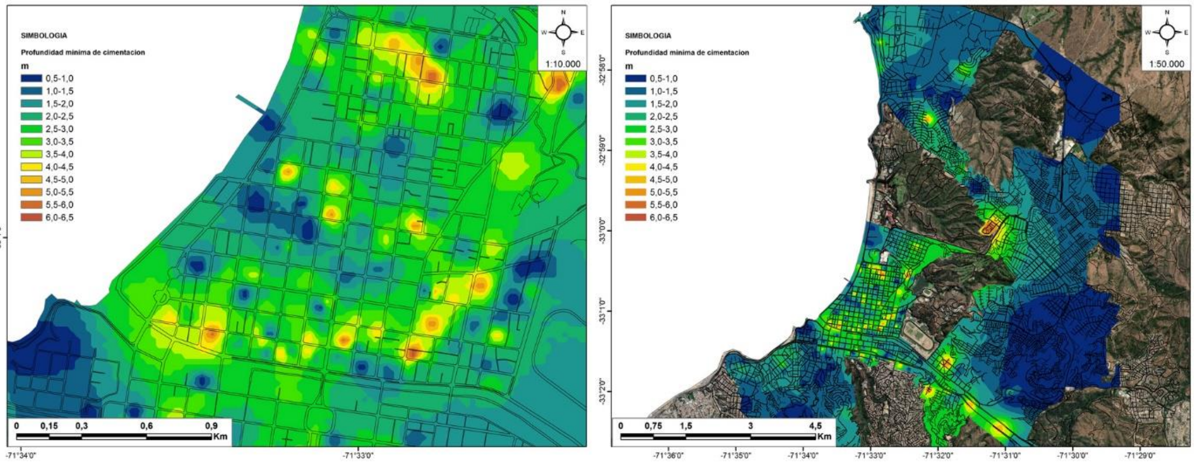

Fig. 6 – Maps of minimum foundation depth for City Plan (left) and for the entire Commune of Viña del Mar (right).

6. Classification of ground surface structure: NSPT and V_{S30}

The shear velocity (Vs) is a fundamental parameter for characterization of ground conditions and it is not easily obtained without adequate field research. The correlations between Vs and penetration resistance proposed by Hasancebi & Ulusay [13] have been chosen for this study. They seem the most suitable relationships once compared to some laboratory tests that have direct Vs and NSPT.

Using this correlation, shear velocities for sandy soils would be estimated as $Vs = 90.82\ (Nspt)^{0.319}$, velocities for clay soils would be $Vs = 97.89\ (Nspt)^{0.269}$ and we should take $Vs = 90.00\ (Nspt)^{0.308}$ for a general (undefined) type. Soils were classified into categories according to the Chilean seismic code, modified in 2011 after the earthquake of February 27, 2010 [4].

With the information obtained from the Cone Penetration Tests (CPT), Standard Penetration Tests (NSPT) and the velocities of propagation of shear waves (direct and calculated Vs for several depths), more than 1.300 graphics showing the ground structure of the soil and subsoil of the Commune of Viña del Mar were made, with a vertical resolution of 0.5 m. Figure 7 shows an example called ID 123 and located in the City Plan.

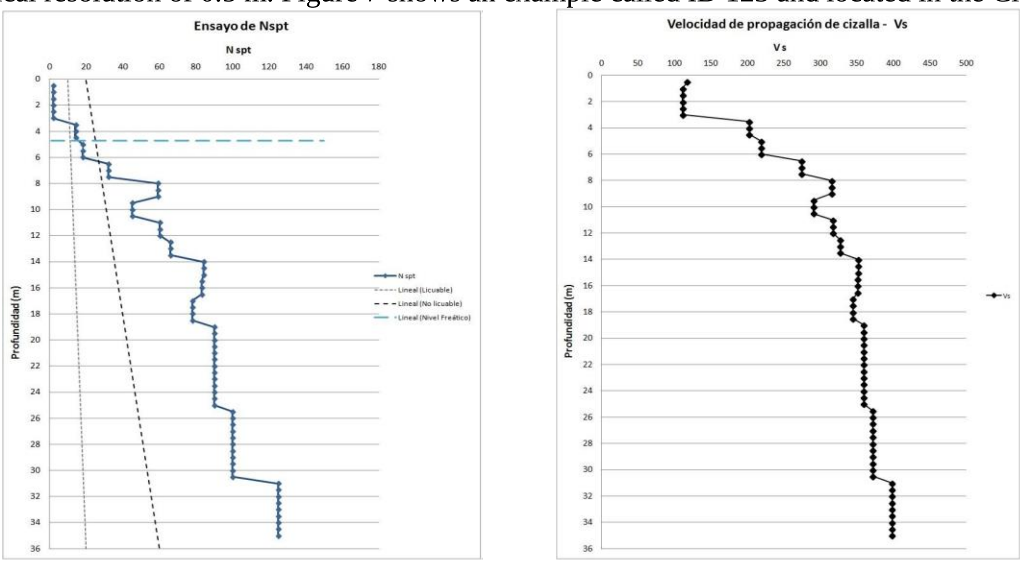

Fig. 7 – Left: NSPT versus depth graph, where the possibly liquefiable range is shown with a thin dotted line. The thickest dashed line shows the range of non-liquefiable soil and the horizontal (cyan) line the depth of the water table. Right: Graph of Vs versus depth, with increasing velocity (hardness) as the depth increases.

Obtaining the Vs structure of the ground in each of the surveys from direct measurements or from NSPT values as was proposed by Hasancebi & Ulusay [13], allowed us to obtain the thickness of soft soils (Vs ≤ 180 m/s) and that of dense or medium firm soils (Vs ≤ 350 m/s) and its variation throughout the Commune of Viña del Mar, especially in the area of the City Plan.

Figure 8 shows the thickness of the layer with average $V_S \leq 180$ m/s, which corresponds to soft soils (type E of the Chilean earthquake resistant standard Nch433, and type D of EC-8, [14]. This thickness is less than 3.0 m in 90% of the City Plan area and more than 6 m in some points in zones near the Marga Marga and Reñaca estuary. (Figure 8 left)

Fig. 8 – Thickness of soils with average Vs ≤ 180 m/s

Similarly, Figure 9 shows the depth reached by soils with average Vs ≤ 350 m/s. The thickness of the layer with Vs < 350 m/s reaches 12 m in more than 80% of the area of Vine Plan and more than 18 m in many surveys near the Marga Marga estuary.

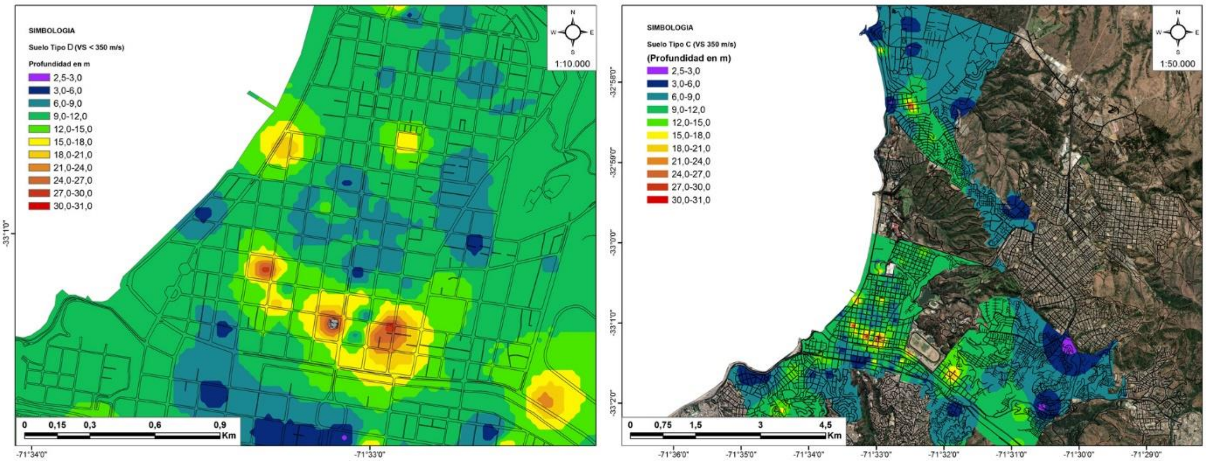

Fig. 9 – Thickness of soils with average speed Vs≤350 m / s

When classifying the soils in terms of the parameter Vs_{30}, the area of the City plan is of type D according to the Chilean earthquake resistant standard [10] whereas the surrounding hills are of soil type C.

Obtaining the average Vs down to depths of 10, 20 and 30 m (Vs_{10}, Vs_{20} and Vs_{30}) (Figures 10) is of great interest in seismic engineering, especially Vs_{30}. This parameter is used in seismic codes for soil classification and thus determines the coefficients or site factors applicable in the seismic-resistant structure design.

The Vs_{10} has been estimated at 327 points distributed throughout the city. In the Plan area, 206 points have been considered with Vs_{10} values varying between 130 and 371 m/s (upper panels in Figure 12) with an average value of 238 m/s. The Vs_{20} has been calculated at 154 points in the commune and in 102 points in the Plan zone, with Vs_{20} values varying between 179 and 447 m/s (277 m/s on average, central panels in Figure 12). The Vs_{30} has been estimated in 93 surveys throughout the study area, obtaining values for the Plan area that vary between 194 and 492 m/s, with an average value of 293 m/s (lower panels in Figure 12).

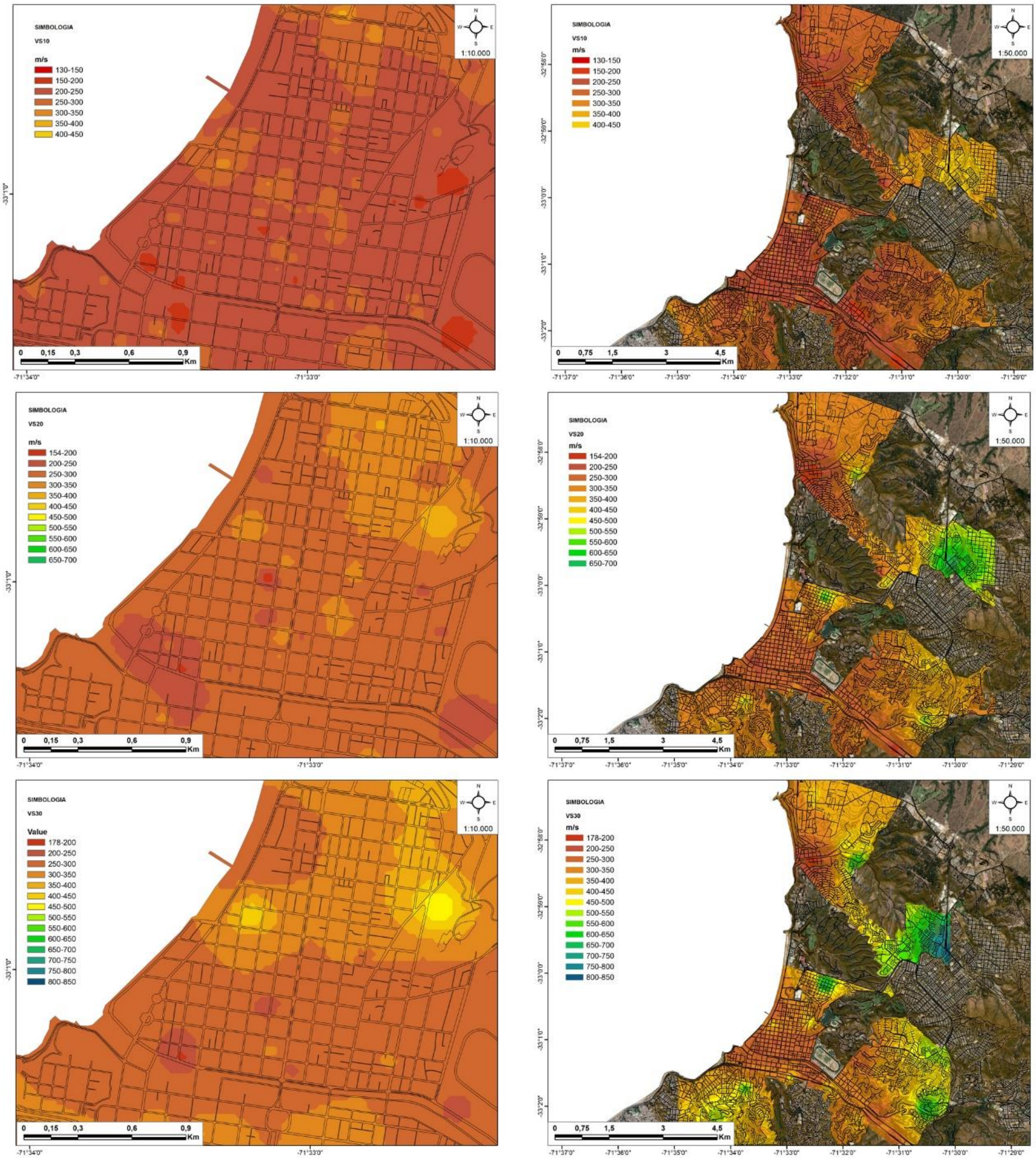

Fig. 10 – Values of V_{S10} (top), V_{S20} (center) and V_{S30} (bottom) obtained from NSPT od from direct measurements of Vs.

The classification mainly based on the description of sediments near the surface (typically in the upper 30 m of sediments) and on the parameter Vs_{30} is currently being questioned and discussed. This parameter may not be sufficiently representative of the ground behavior for sites with sedimentary soils with thicknesses greater than 30 m. Despite this, the seismic-resistant regulations in force in Chile (Nch433Of96mod2009, Dto61 article 5), consider Vs_{30} as a valid simplified parameter to classify the soil.

Because this seismic microzonation study is established in the Chilean regulatory framework, it has been considered essential to accept what is established in the current seismic-resistant norm, bearing in mind that there are other alternatives to classify the ground structure, such as inferring the velocity to a depth z > 30 m (Vsz) using empirical relations Vsz-Vs_{30} [15], through the predominant period of the soil, or the depth of the basement Hb [8], among others.

Despite the above, it should be noted that this is the first time in Chile that a Municipal Public Institution is developing a seismic microzoning study based on the available, open and transparent information existing in the Municipal Works Directorate, which is being included in the preparation of the new Regulatory Plan of the Commune of Viña del Mar.

7. Conclusions

- From the analysis of the seismicity, it follows that the large interplate earthquakes are the ones that contribute most to the seismic hazard in Viña del Mar area. The review of the destructive earthquakes of the twentieth and twenty-first century that affected the city, especially those of 1906, 1960, 1985 and 2010, show the record the sedimentary areas where damages are consistently repeated and demonstrate the influence that these conditions have on such damage distribution.

- The information extracted from the 440 mechanical surveys has allowed to obtain the parameters used for soil classification (for example granulometry and its classification according to the USCS and Atterberg limits) and geotechnical parameters (for example NSPT, cohesion, internal friction angle, relative density, specific weight, liquid limit, plasticity index and Poisson coefficient) and to characterize with them the four most abundant USCS soil units in the first 10 m, represented on a map that constitutes a first geotechnical microzonification of the urban area.

- Using the relationship proposed by Hasancebi & Ulusay [13] the V_S structure has been determined down to a depth of 30 m. The shallow layer of soils with $V_S \leq 180$ m/s represents less than 3.0 m in 90% of the flat area and extends down to more than 6 m in areas near the Marga Marga and Reñaca estuary. The layer with $V_S \leq 350$ m/s has a depth larger than 12 m in more than 80% of the City Plan, and it exceeds 18 m in many of the surveys.

- The average velocities of shear waves Vs_{10}, Vs_{20} and Vs_{30}, corresponding to the upper 10, 20 and 30 m, have been calculated. In the City Plan, Vs_{10} varies between 130 and 371 m/s and presents an average value of 238 m/s; Vs_{20} varies between 179 and 447 m/s with average of 277 m/s and Vs_{30} varies between 194 and 492 m/s with an average value of 282 m/s.

- The Vs_{30} parameter is of great interest in seismic engineering, as it is a synthetic expression of the dynamic properties of a soil profile, considered suitable in the NCH433 norm to quantify the influence of the local ground conditions in the elastic response spectrum. Classifications of the soil by distributions of Vs_{30} should be regarded as a simplified method. Most of the analyzed sites located in the City Plan are of type D, varying in a few cases to type C. The hills are of type C with some small areas of type B [4].

- We hope to incorporate more detailed information of the soil structure in the database created by the Municipality of Viña del Mar for public consultation in the near future. The database currently includes lithological description every 0.5 m down to the depth of each survey, 338 stratigraphic columns and more than 1,300 graphics of CPT, Nspt and Vs as a function of the depth. Note that Nch1508-14 [16] requires a geotechnical study for each projected building.

- The reason why the parameters NSPT and Vs_{30} were chosen as soil characterization and incorporated in the methodology presented here, is mainly due to the fact that the Municipalities do not have sufficient resources to carry out laboratory tests, down-hole, cross-hole surveys, surface (Rayleigh) wave measurements (SASW, MASW or ReMi), etc. However, they have abundant technical information within the building reports, including studies of soil mechanics. Through the systematization of this information and its parameterization, risk areas can be defined for the new regulatory plan of the city.

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