MAP OF SEDIMENT THICKNESS AS PRIMARY INPUT FOR THE CARACAS SEISMIC MICROZONING PROJECT

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ABSTRACT

The location of Caracas close to the plate boundary between the South American and the Caribbean plates, the emplacement within a sediment filled half graben, and the extensions on steep hills are responsible for the moderate to high seismic hazard in the city. During the Caracas 1967 earthquake, strong but localized basin effects contributed to the damage distribution of high rise buildings within the sedimentary valley. Seismic refraction profiles done right after the earthquake allowed determination of the depths to bedrock to about 350 m. Within the scope of the Caracas seismic microzoning project (done in the years 2005-2009), detailed 3D gravimetric modeling was performed, integrating all the available subsurface information for Caracas valley, as there are depth to bedrock and seismic velocities from the 1968 and 2001 seismic refraction surveys, information from water wells from different times (1950ies to recent), geotechnical and stratigraphic drillholes, and depth estimates from predominant periods. More than 1000 gravity points were re-processed and modeled along 50 parallel vertical planes for a 3D subsurface image of the valley. The resulting information is displayed for 4 depth ranges (0-60, 0-120, 120-220 and > 220 m), according to the scope of parametric dynamic soil response analysis, and used as the base for the definition of the limits between zones of similar seismic response within the valley.

Keywords: Sediment thickness, seismic refraction, gravimetric modeling, seismic microzoning, site effects.

INTRODUCTION

The main objective is to upgrade and integrate the information provided by geophysical measurements (gravimetric, ambient seismic noise and seismic refraction) with the geological information and well logs from different eras, to characterize and quantify the thickness of the sedimentary layer in the Caracas Metropolitan Region, as these results provide important input information for calculating the dynamic soil response. The study area includes the entire Caracas Metropolitan Region, in the central region of Venezuela, at the foot of the Ávila mountain (figure 1). The Caracas valley is considered morphologically and tectonically a semi-graben, separated from the massif by Tacaugua-El Ávila fault system, according to geological evidence (triangular facets). These phenomena may be the indirect result of seismic activity associated with the transform faults that delimit Caracas semi-graben (Singer, 1977).

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The first of a number of publications regarding the soil and engineering effects of the Caracas 1967 earthquake (Sozen et al., 1968) contains a map of sediment thickness of the Caracas Valley. This map was based on geological and sedimentary thickness data from feasibility studies for the construction of the Caracas Metro (Pérez y Pérez, 1961; Pérez, 1967). According to these results, in the western part of the valley (San Bernardino; figure 1) sediment thickness achieves 120 m, while in the eastern part of the valley, a maximum thickness of 80 m is reached south of Los Palos Grandes. This map of sediment thickness, with a sediment thickness of 60-80 m in the southern part of Los Palos Grandes, where structural damage and collapse of buildings is concentrated, did not help to understand the damage distribution, as similar sediments thicknesses were reported from other parts of the city without increased damage to buildings.

Figure 1. Map of sediment thickness in Caracas valley and location of damaged buildings (open circles: structural damage, black circles: difficult to repair and collapse) due to the 1967 Caracas earthquake for the western part of the valley in San Bernardino (left) and the eastern part with the maximum values south of Los Palos Grandes (right) (Sozen et al., 1968).

Whitman (1969) presents a map of sediment thickness indicating a maximum depth to bedrock of 300 m in the eastern part of the valley in Los Palos Grandes (Figure 2), based on seismic refraction measurements (Murphy et al., 1969), and contracted by the Presidential Commission for the Study of the Earthquake. In the seismic refraction study a total of 14 seismic profiles were done in the valley, as well as 5 geotechnical drillings with crosshole measurements in the area of Los Palos Grandes, resulting in the distribution of P and S waves and the geometry of basement rocks and sedimentary thickness in the valley of Caracas (Murphy et al., 1969). The primary objective in these studies was to determine the different soil conditions that may be responsible for the variation of intensities of damage caused by the earthquake of 1967.

A further study, which relates soil conditions and the buildings collapsed during the earthquake of Caracas (Seed et al., 1970), was published a year later, and refers to Whitman's (1969) report and to the seismic results (Murphy et al., 1969). Although the shape of the sediment distribution and the related damage pattern that were analyzed in this work (Figure 3) are similar to the one reported by Whitman (1969), the absolute sediment thickness reported for Los Palos Grandes region is much less with 230 m (Figure 3). To this point it is not clear, what is the origin of this difference in sediment thickness displayed in both reports. Nevertheless, the main outcome, a clear relationship between the depth to the bedrock and the damage distribution had been evidenced by the reports published soon after the earthquake.

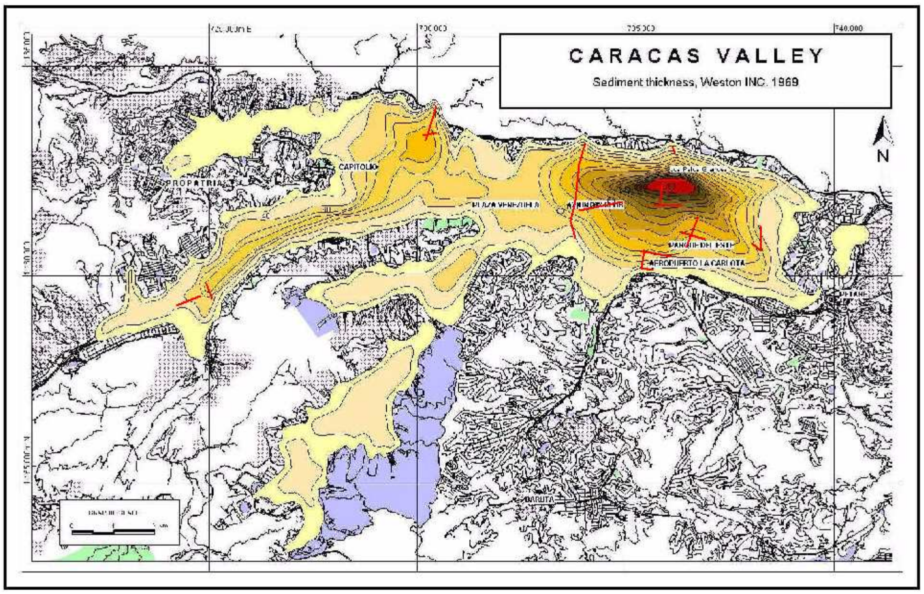

Figure 2. Map of sediment thickness in Caracas valley and location of seismic lines (after Whitman, 1969, based on seismic lines from Murphy et al., 1969).

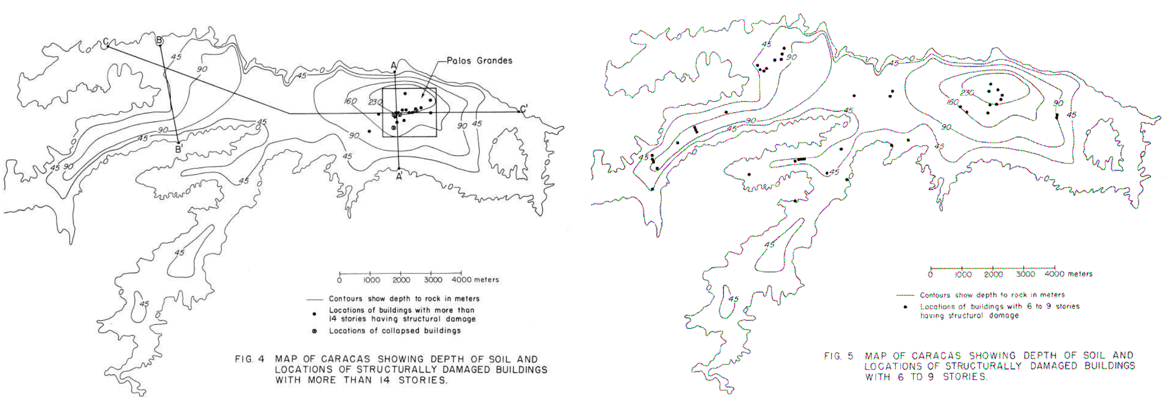

Figure 3. Map of sediment thickness in Caracas valley and location of damaged buildings (structurally damaged buildings with more than 14 stories, left, and with 6 to 9 stories, right) due to the 1967 Caracas earthquake (Seed et al., 1970).

Kantak et al., (2005) present the results of a compilation based on drilling information, mostly for groundwater exploration (Delaware, 1950, Pérez, 1961; and Hidrocapital, pers. com.). This study confirmed the existence of two depressions in the bedrock surface, one of more than 300 m located in Los

Palos Grandes / Santa Eduvigis in the east, and a second one in San Bernardino in the west that reaches 140 m. Neverheless, the location of the deepest borehole that reached bedrock at 300 m is not exactly documented.

The importance of the relation between sediment thickness and damage distribution, which was reported already in earlier local works (e.g. Grases, 1968), caused attention also to the community that worked on the modeling of the propagation of seismic waves. The model derived by Papageorgiou and Kim (1991) allowed to construct realistic spectra for different depth ranges along a profile in Los Palos Grandes, including the effect of attenuation of the soils. Further work on the modeling of the seismic response along 2-D profiles crossing the valley (Semblat et al., 2002; Schmitz et al., 2002) evidenced the need for a more detailed subsurface model.

GRAVITY MEASUREMENTS

Approximately 1600 ordinary gravity stations in the valley of Caracas have been measured with a spacing of approximately 250 meters between stations (Sánchez, 2001; Lara, 2004; Moncada, 2005; UCV, 2005). To each of the stations, Free Air, Bouguer and topography corrections were applied in order to remove all the effects that may alter gravity measurements, remaining the sole cause of the alteration of the lateral variations of density at subsurface (Figure 4).

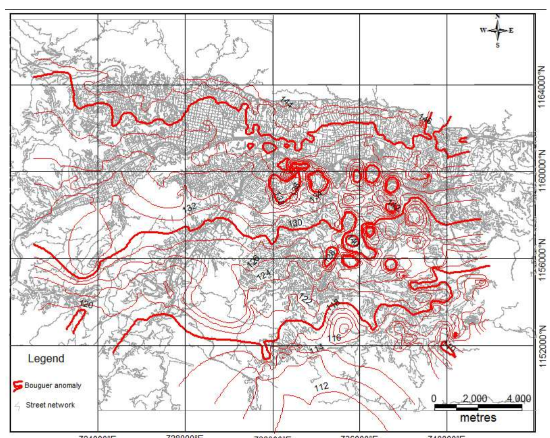

Figure 4. Bouguer isoanomaly of Caracas valley for a Bouguer density of 2.44 gr/cm^3 and an elevation of 850 m.a.s.l.

The Bouguer isoanomaly curves (Figure 4) show a very marked east - west trend. The highest values are found in the north of the study area with a value of 144 mgal and a smooth gradient of 2.14 mgal/km, decreasing south to a value of 122 mgal. In the northwest and the northeast, the distorsion of the isolines aligns well with the San Bernardino and Los Palos Grandes basins, respectively. In the southwest, a positive anomaly is related to the presence of a topographic high between La Vega and the Pan American Highway with outcropping schists (Moncada, 2005). Finally, in the southeast, specifically in the Baruta and El Hatillo municipalities, the lack of topographic control of the gravity data in the rugged topography area is responsible for a number of small anomalies which are not consistent with the rest of the gravimetric data.

Regional component and residual Bouguer anomaly

The regional component (Figure 5) shows an east – west trend with a maximum value of 148 mgal north and a gradient of 2.25 mgal/km, decreasing south with a minimum value of 128 mgal. This trend is attributed to the strike of the main structures of Caracas valley, bounded by the Ávila fault. To determine the values of the residual component of the Bouguer anomaly, a regional-residual separation was conducted using the method of polynomial approximation. Polynomial regression was performed from the Bouguer anomaly data for different types, later defined qualitatively and quantitatively (due to goodness of fit) a regression of third order, being the best correlation with geological structures present in the area. The residual component (Figure 5) manages to highlight two major residual effects previously observed in the Bouguer anomaly (Figure 4). In the San Bernardino area, a minimum value of -2 mgal corresponds to a value of 138 mgal in the Bouguer anomaly. Likewise, in the Los Palos Grandes area a minimum of -3 mgal coincides in location with a minimum of 142 mgal observed in the Bouguer anomaly. The location of these minima coincides with the region where the greatest sediment thickness is observed. Again, the area with rough topography in the southeast is characterized with a los of small anomalies, which are considered to be due to errors in the topographic data.

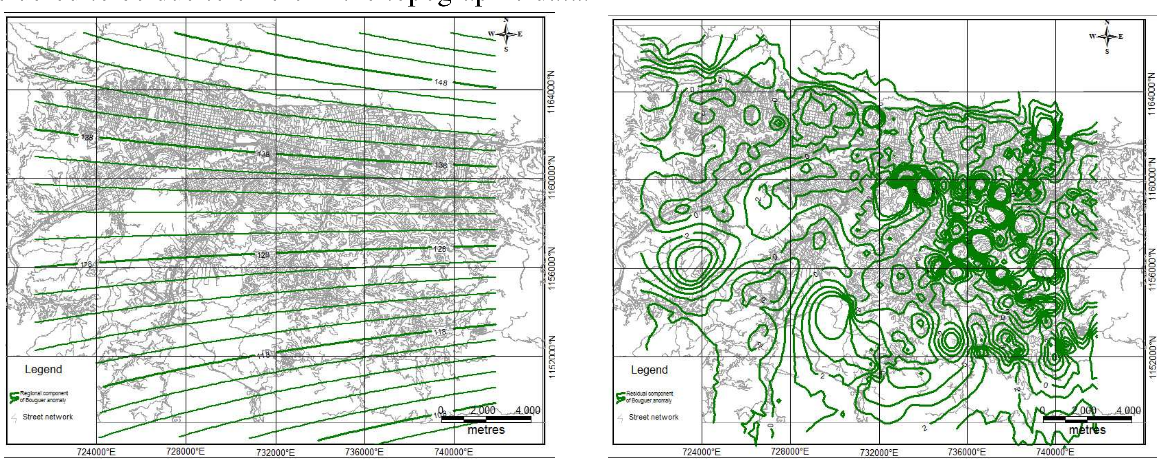

Figure 5. Regional (left) and residual component (right) of Bouguer anomaly in Caracas valley.

SEISMIC MEASUREMENTS AND DRILLINGS

Seismic surveys conducted include deep seismic refraction measurements and in situ measurements of shear wave velocity in the Caracas valley (Figure 6). These studies were made in 1968, shortly after the 1967 Caracas earthquake (Murphy et al., 1969), and later in the year 2001 (Sánchez et al., 2005). The primary objective of these measurements was to determine the different site conditions that could be correlated with the varying damage intensities. Seismic profiles were conducted in various areas within the valley, so that a comparison could be established between areas of intense damage and little damage, as established by detailed investigations done within the scope of the Presidential Commission for the Study of the Earthquake (Briceño et al., 1978). The seismic profiles are located in the areas of Los Palos Grandes, Parque del Este, La Carlota airport, Tocome, Caracas Country Club, La Castellana, San Bernardino, La Vega (Urb Montalban) and Urb La Paz (Figure 6).

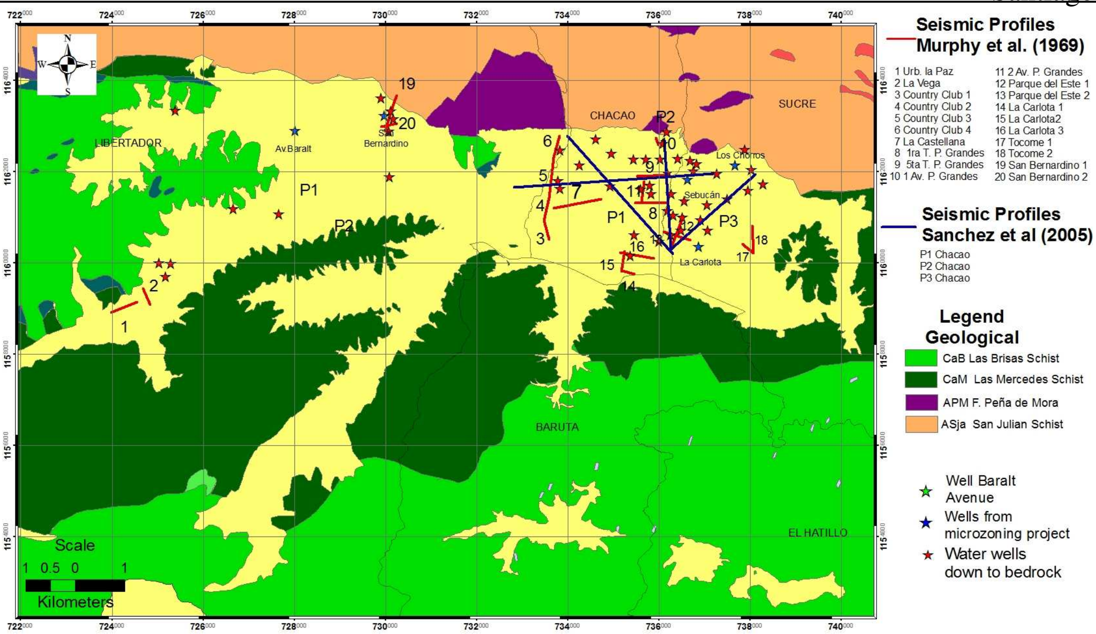

Figure 6. Bedrock geology (Urbani y Rodríguez, 2004), location of wells, and seismic profiles within Caracas valley.

The longest profile of the 1968 measurements was made in the Caracas Country Club with approximately 2.5 km from north to south, located west of Los Palos Grandes (the region with damage concentration o high rise buildings). The sediment thickness for most of the profile is in the order of 125 m, with a decrease to 40 m in the southernmost part. On the other side of Los Palos Grandes, in the field of Tócome (to the east), the top of the bedrock is located at a depth between 60 and 100 m. A number of profiles within the basin of Los Palos Grandes allowed derive a detailed map of sediment thickness for this area. Three seismic profiles of more than 500 m length all pointed to a thickness of 300 m. According to the results of the seismic sections of Parque del Este and La Carlota airport in the southern part of Los Palos Grandes, a shallowing of the depth to bedrock to the south, with 170 m in the north and a minimum of 20 m its southern part (close to the Guaire river), was confirmed. This information is consistent with a geotechnical drilling in La Carlota (GISCA, 2006), done within the scope of the Caracas seismic microzoning project. A short profile (200 m in length) very close to the boundary between the city and the Avila mountain, pointed to a thickness of approximately 100 m. A drilling (Los Chorros), done about 2 km east in a similar position regarding the edge of the basin, reached bedrock at 220 m. In the center of the basin (Sebucan), a drilling was done down to 280 m, without reaching bedrock (GISCA, 2006). The 1968 seismic data allowed derive P-wave velocities for 4 strata, soil down to 15-50 m depth with 400-900 m/s, water saturated sediments with about 1800 m/s down to 100-150 m depth, and below consolidated sediments with 2400 m/s down to the bedrock with 3800-4000 m/s (Murphy et al., 1969).

Additionally, direct measurements of shear wave velocities have been done in a crosshole array of 6 drillings down to 70 m in the Los Palos Grandes region (Carrillo and Pérez, 1978). Shear wave velocity is 430 m/s in the depth range 15 to 70 m, and below this value in the upper part. In order to constraint the shear wave velocities in the valley, seismic measurements were done in 2001 in the eastern part of the valley along 4 profiles crossing the deeper structure of the Los Palos Grandes basin (Sánchez et al., 2005). As further argument for the measurements in 2001 was to constrain the detailed geometry of the basin, as the original data from the 1968 measurements were no longer available. Derived shear wave velocities were 450 m/s for the upper 15 m and 860 m/s for the sediments below, and approximately 2500 m/s for the bedrock (Sánchez et al., 2005). We suggest a shear wave velocity in the depth range 15 – 100 m of 650 m/s based on estimates from the application of the relationship Vs=4H/T (Kramer, 1996) to ambient noise measurements in Caracas (Schmitz et al., 2003). Cornou et al. (2010) conducted studies of ambient seismic noise arrays at 5 sites within the sedimentary valley of Caracas. Reported shear wave velocities range between 200-500 m/s for near surface layers (upper 30 m) and 500-800 m/s below.

For San Bernardino, previous models (see figures 2 and 3) propose a sediment thickness of up to 140 m, based on the seismic results (Murphy et al., 1969). Nevertheless, a recent geotechnical drilling in the same region reports a depth of 210 m, without reaching bedrock (but with indications to be close to the top; Vangil, 2007). Although the original seismic data from 1968 do no longer exist (only the results are provided in the report) we may infer that the top of the consolidated sediments was interpreted as top of the basement in San Bernardino, as both discontinuities provide prominent velocity changes. In addition, there were two sections in the west of the city of Caracas, in La Paz and La Vega, where the seismic profiles indicate a sediment thickness of up to 100 m (Murphy et al., 1969).

ISOPERIODS

Since the mid-90's, ambient noise measurements were done in Caracas by various research groups (e.g. Abeki et al., 1995; 1998; Semblat et al., 2002), in order to obtain the predominant periods of soil using the H/V method (Bard, 1999). A clear relationship between sediment thickness and predominant periods, as already stated by previous works in Caracas (e.g. Briceño et al., 1978; Papageorgiou and Kim, 1991), was the fundamental outcome of these studies. Today, a total of 2000 ambient noise measurements have been accumulated in Caracas (e.g. Enomoto et al., 2000; Rocabado et al., 2006), which are separated on average every 250 m. The values obtained for the periphery of the Caracas valley range between 0.25 and 0.3 s, indicating weathered bedrock or low sediment thicknesses. Within the sedimentary valley, periods range generally between 0.5 and 1 s, being considerably superior to 1 s in two areas of the valley (San Bernardino and Los Palos Grandes) with maximum values of 1.6 s for San Bernardino and 2.1 s for Los Palos Grandes, respectively (Rocabado et al., 2006; Figure 7).

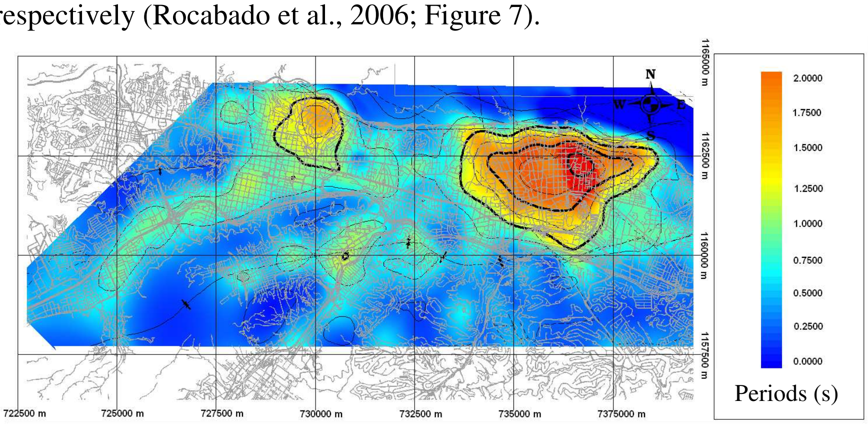

Figure 7. Isoperiods from ambient noise measurements in Caracas valley (Rocabado et al., 2006).

GRAVITY MODELING

The gravity modeling was done with the program IGMAS (Magnetic Gravity Interactive Application System) (Götze and Lahmeyer, 1988, Schmidt and Götze, 1998), which generates 3D models from 2D multi-dimensional sections. The initial model was generated from two-dimensional gravity modeling information by Sánchez (2001) and Moncada (2005), the geological map (Urbani and Rodríguez, 2004) and the map of fundamental periods of the city of Caracas (Rocabado, et al., 2006). For information on depth to bedrock, a collection of well data provided by Hidrocapital, and referred to in Kantak et al. (2005) and Moncada (2005), as well as 4 drillings from the Caracas seismic microzoning project to depths of 129 m, 220 m, 280 m and 210 m, respectively (the last 2 failed to reach bedrock), and a well provided by the Metro de Caracas, CA located in the west of the valley, which reached rock at a depth of 70 m (see figure 6) was used. Similarly, we used the results of seismic measurements (Murphy et al., 1969; Sánchez et al., 2005).

The densities of the metamorphic units were adjusted from Moncada (2005), the lithological description of the geological units, and finally from interaction with the IGMAS program, which manages a tool of physical parameters, adjusting the density of Quaternary sediments at a value of 1.8 gr/cm^3. The density of the Quaternary sediments, which varies by 0.4 g/cm3, is the most different from those used by Moncada (2005), which were 2.2 gr/cm^3, whereas the densities for the bedrock were kept similar. A reason for the considerable differences in the density of the Quaternary sediments might be the difference in 2D Moncada (2005) versus 3D (this contribution). A total of 50 2D sections were generated, which allowed giving a comprehensive and detailed representation of the geological units present in the study area. Gravity values of the residual component of the Bouguer anomaly were compared with values calculated by the IGMAS program, and differences adjusted by variations in the density model. Figure 8 shows a typical 2D section, with the Quaternary sediments, surrounding bedrock (Las Mercedes, Las Brisas and San Julian schists) down to about 500 m depth and constraining information (drill holes). The final adjustment of the model was 85% correlation between measured and modeled data, giving a good reliability of the model.

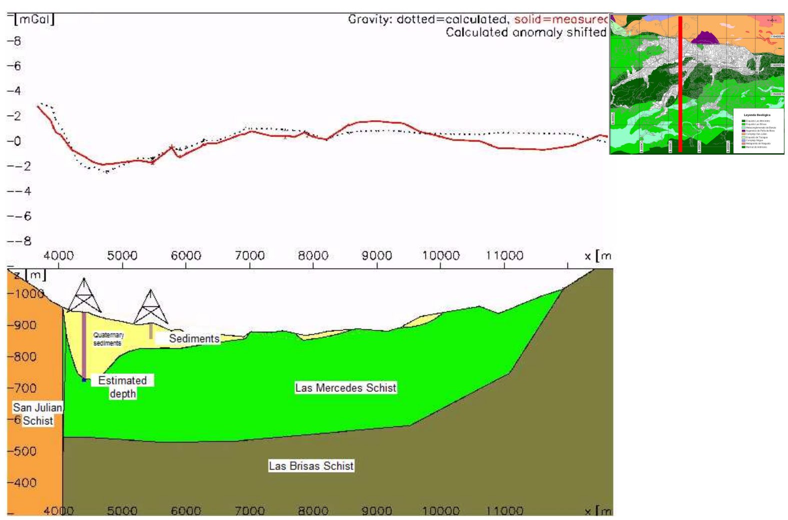

Figure 8. Typical 2D profile of the 3D IGMAS model, showing the location of the profile in the inset.

SEDIMENT THICKNESS

From 3D modeling, a map of the sediment thickness was generated (Figure 9), using the application IVIS3D from the IGMAS program, which generates a data table with the depths points of the contact between Quaternary sediments and bedrock, which is then interpolated applying a kriging interpolation method to obtain the sediment thickness contours. The deepest part of the sedimentary basin is located in the eastern part of the valley, in Los Palos Grandes, with 360 m. In the center of the valley the basin flattens and reaches in the area of San Bernardino in the west 260 m, proven by a geotechnical drillin g of more than 210 m at Hotel Avila. The resulting information is displayed in four depth ranges with three steps (0-60, 60-120, 120-220 and >220 m) (Figure 9), according to the depth classes defined by a parametric study of the dynamic soil response done in the scope of the Caracas seismic microzoning project (Hernandez et al., 2010). This map was then used as a base for defining the boundaries between areas of similar seismic response within the valley (Schmitz et al., 2011).

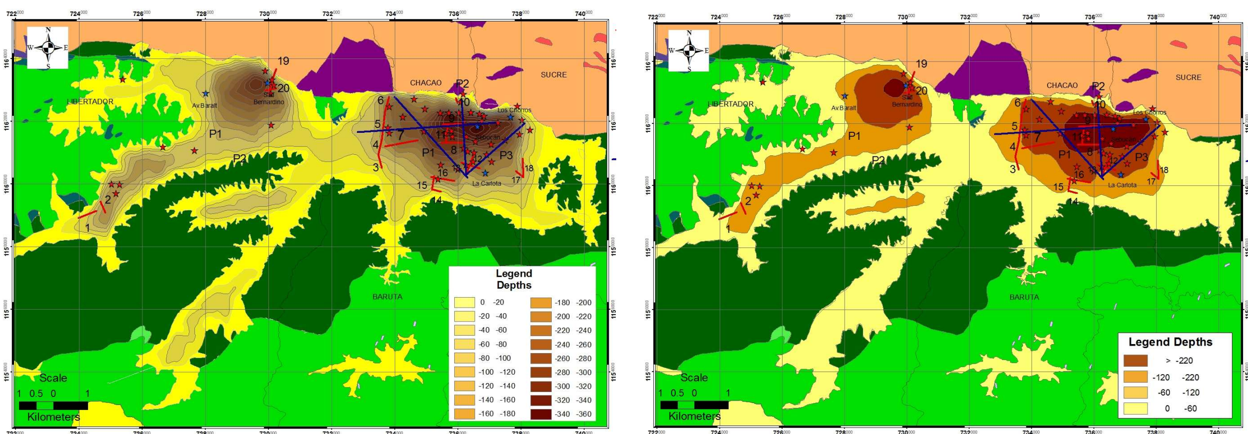

Figure 9. Sedimentary thickness of Caracas valley (left) and sediment thickness distributed in 4 classes for definition of microzones (Schmitz et al., 2011) (right).

CONCLUSIONS

The construction of a 3D sedimentary thickness model for Caracas valley was done through the integration of geological, geophysical and drilling information in order to generate a map of sediment thickness for the Caracas Metropolitan Area. The analysis of the results of ambient seismic noise (isoperiods), from seismic refraction studies and drilling information allowed adjust and calibrate some sections of the 3D gravity model. Re-interpretation and integration of old (1968) seismic data gave helpful constraints for the model configuration. The residual Bouguer anomaly, a third-degree polynomial approximation, shows two areas of specific interest, one in the west with values between -2 to -3 mgal and one in the east with -4 mgal. According to the gravity model, maximum thickness is 260 m in the San Bernardino basin and 360 m in the Los Palos Grandes basin. Although the obtained values are in the range of the previous models for Los Palos Grandes, changes are significant for San Bernardino, and in general regarding the geometry of the bedrock-sediment interface, an important boundary with a significant impedance contrast, that controls the distribution of the amplification of seismic waves within

Caracas valley. The 3D model procedure allows us to integrate previously observed gravimetric data together with other constraining information. There is a good correlation between areas of negative residual Bouguer anomaly, high values of predominant soil periods a deeper rock-sediment interface. Within the scope of the Caracas seismic microzoning project this information is used for assigning microzones of similar seismic response with specific design spectra.

AKNOWLEDGEMENTS

Study realized within the scope and with funding from the "Proyecto de Microzonificación Sísmica en las Ciudades Caracas y Barquisimeto" (FONACIT – BID II 2004000738). We express our gratitude to the staff of FUNVISIS and outside the institution that collaborated in carrying out this work.

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