

GEOPHYSICAL STUDIES IN BARQUISIMETO METROPOLITAN AREA, VENEZUELA, AS CONTRIBUTION TO A SEISMIC MICROZONING STUDY

Víctor ROCABADO¹, Michael SCHMITZ¹, Javier SANCHEZ¹ and Carlos REINOZA¹

ABSTRACT

During the last two years, in Barquisimeto Metropolitan Area, microtremors, gravimetry and seismic refraction measurements were done in order to identify the shape and depth of the basin, and evaluate the ground shaking characteristics. The predominant periods obtained from H/V analysis vary between 0.2 to 3.0 s, with a maximum of 0.8s in Barquisimeto and 3.0s in Cabudare. Associating the values of periods with sediment thickness it was possible to estimate the maximum depth of sediments in Barquisimeto to 80-110 meters, and in Cabudare to 400 meters. These results show a good correlation with observed Bouger anomaly with a minimum of -34 mGals in Cabudare, which corresponds to high sediment thickness. The subsoil information from geophysical studies will be used to define the distribution of microzones of equal seismic response based on typified response spectra.

Keywords: Microzoning Studies, Microtremors, Gravimetry, Seismic Refraction

INTRODUCTION

The Barquisimeto Metropolitan Area is located in western Venezuela. The local tectonic situation is characterized by the vicinity of the Boconó fault, as part of the plate boundary zone between the South American and Caribbean plates, with a main fault system with dextral strike-slip movements of about 1-2 cm/year (Figure 1).

The Boconó fault had originated several destructive earthquakes being the 1812 earthquake the most remarkable one, which caused some 4.000 fatalities in Barquisimeto (Grases, 1990). Currently, Barquisimeto is a fast growing city with over one million inhabitants, expanding mainly over old river terraces. Cretaceous formations outcrop in eastern Barquisimeto, where recent urban development has been concentrating. On the other hand terraces with up to 100 meters thickness are present in the west, where industrial and informal housing areas are spreading.

This study is part of a microzoning project that started in 2005 in cooperation with the local government and the Lara state administration. A crucial phase in the project is the definition of microzones of equal seismic response (Hernández et al., 2006; Schmitz et al., 2007). Based on generic soil models with variations of sediment thickness, and shear wave velocity for the upper 30 m (V_{s30}), response spectra are calculated, considering the seismic hazard in the area. These response spectra are typified regarding the predominant period and the shape of the spectra. Then, the typified spectra are associated to the corresponding microzones regarding their geological and geophysical characterization, derived by the geophysical investigations presented in this contribution. The definition of the microzones

¹ Geophysics Engineer, FUNVISIS, Venezuelan Foundation for Seismological Research. Email: vrocabado@funvisis.gob.ve

will be calibrated with the distribution of predominant periods from ambient noise measurements, results of 2D and 3D seismic response calculations, and detailed dynamic models and experimental transfer functions based on drilling information (from 100 to 300 m depth). Active participation of public engineers in the evaluation of subsoil data as well as building characteristics for vulnerability assessment is an important part of this seismic microzoning project (Hernández et al., 2006). A general knowledge on seismic resistant construction shall be introduced to the community, in a formal and informal approach.

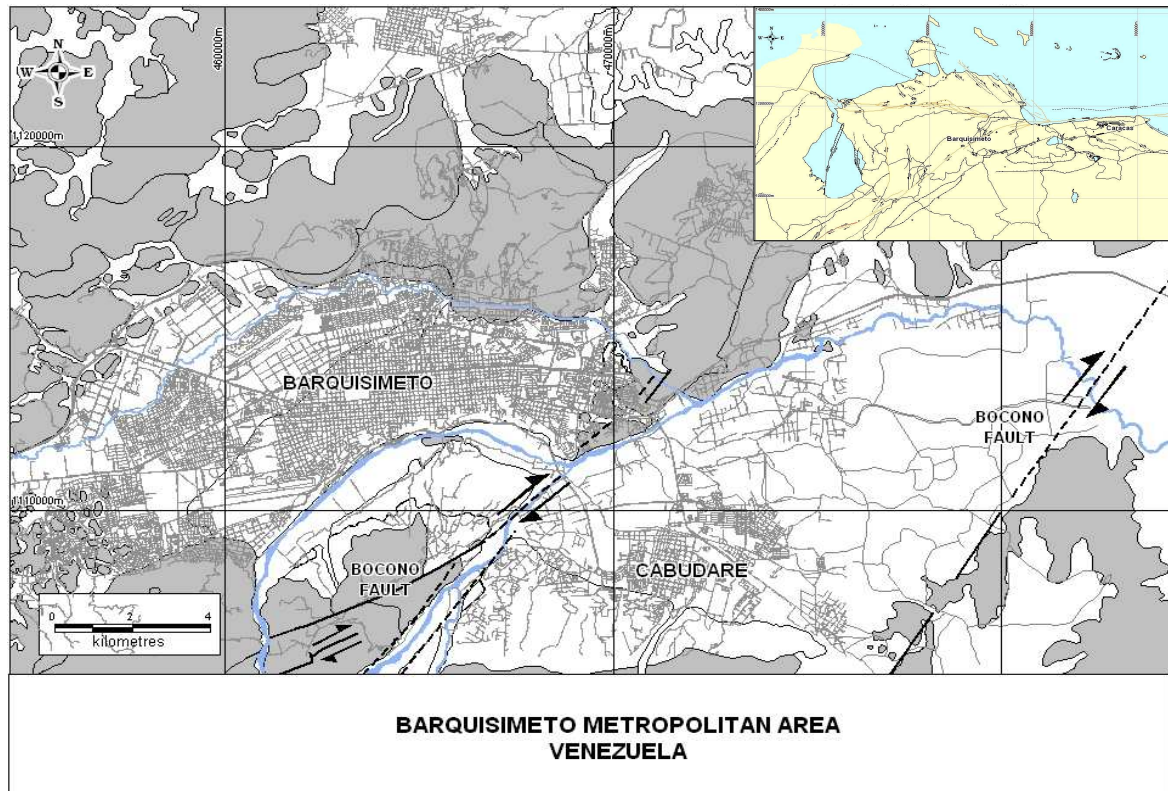


Figure 1. Location of Barquisimeto and Cabudare. The Boconó fault defines a pull-apart basin in Cabudare with Cretaceous bedrock (grey) at the basin edges and Quaternary sediments (white) as basin fill (geological compilation by Bechtold, 2004).

MICROTREMOR MEASUREMENTS

Ambient noise methods are non-expensive and give fast and reliable estimates of site effects. One of the most widely used method is the spectral relationship H/V (Nakamura, 1989; Bard, 1999) introduced by Nogoshi and Igarashi (1971), where the fundamental soil period is interpreted as a predominant peak on ellipticity of Rayleigh waves (Lachet & Bard, 1994; Field & Jacob, 1995; Konno & Ohmachi, 1998), if the impedance contrast between the soft soil and the basement rock is more than twice (Bard, 1999).

The H/V method was applied with good results in previous studies to estimate the natural frequency and sediment thickness (e.g. Ibs-von Seht & Wohlenberg, 1999; Parolai et al., 2001, 2002). The application of this technique in Venezuela in different sedimentary environments in cities with soft sediments like in Cumaná (Abeki et al., 1998a) and Cariaco (Gonzalez et al., 2004), as well as in cities with deep sedimentary basins like Caracas (Abeki et al., 1998b; Enomoto et al., 2000; Rocabado et al., 2001; Semblat et al., 2002; Moros, 2004; Moreno, 2004) evidenced good results. Consistent results were also obtained in other sedimentary environments like alluvial fans in Vargas State

(Romero et al., 2006), fluvial terraces in Mérida State (Palme et al., 2002) and Barquisimeto Metropolitan Area (Rocabado et al, 2002; De Marco et al., 2004, Nobile, 2005).

A total of 460 measurements were carried out in Barquisimeto Metropolitan Area (Figure 2) with a distance of 500m between stations. From this total, 290 stations are located in Barquisimeto area and 170 in Cabudare.

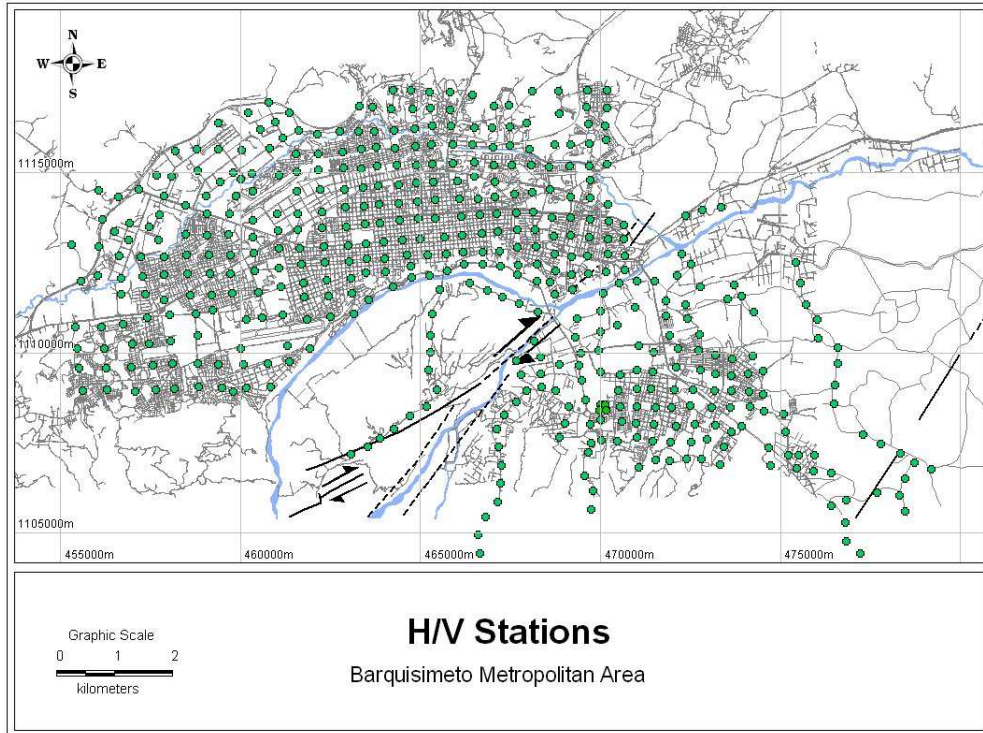


Figure 2. Location of single stations of noise recording, the grid distance was 500m.

The instruments used for acquisition consisted in an Orion-Nanometrics seismograph with a broadband 3-component sensor Guralp CMG-40T. The sample rate was 100 sps and the record length varied between 10 and 20 minutes. In all cases, one of the horizontal components was aligned with north–south direction. Previous to recording, several external conditions were checked to guarantee the quality of acquisition, like: signal stability, sensor location (far from water pipes, electricity and other facilities), and distance to white noise sources (Bard, 1999).

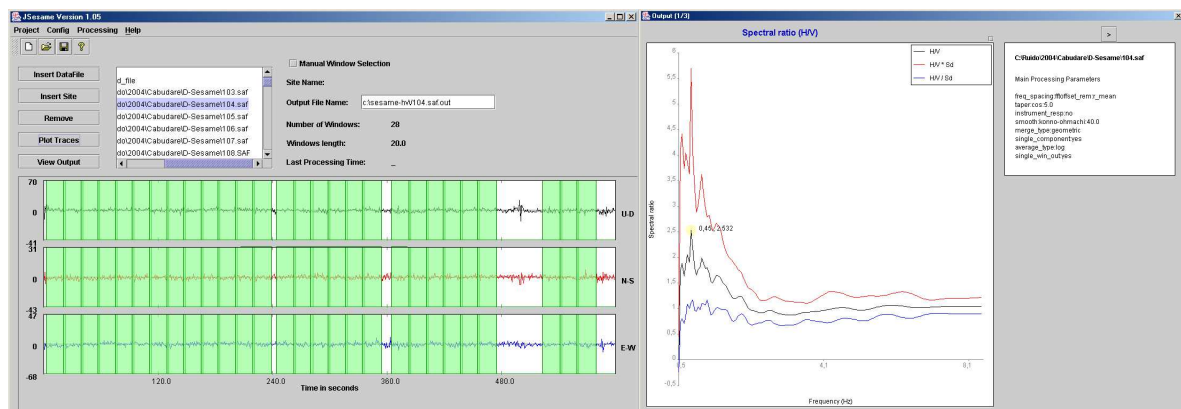


Figure 3. Processing of single station. Left: Selected windows on J-Sesame. Right: H/V curve with selected value.

The J-SESAME program (Site Effects Assessment Using Ambient Excitations) was used for data processing to identify the predominant period of soil response. This program was developed during

the SESAME Project (Bard et al., 2005) in a common effort of several European institutions and universities involved in the project. The program allows selecting several time windows; for each single window the program calculates the H/V ratio and generates a single output that includes the average H/V curve obtained from all the single windows, as well as the standard deviations (Figure 3).

From the results obtained in each single station, it was possible to generate a map of predominant periods for the area (Figure 4). A detailed analysis of the results observed in Barquisimeto city showed that in the eastern and northern areas (foothills) the values in the period range between 0.3 and 0.5s. In western and central areas of the city, the values increase in range from 0.5 to 1.0s; 70% of the measurements result in this range. Toward south, in the Cabudare area, the predominant periods increase drastically, with a maximum of 2.5s in the central area (and increasing towards north-east). The minimum values vary from 0.3 to 0.5s in the south, corresponding to sites in the foothills.

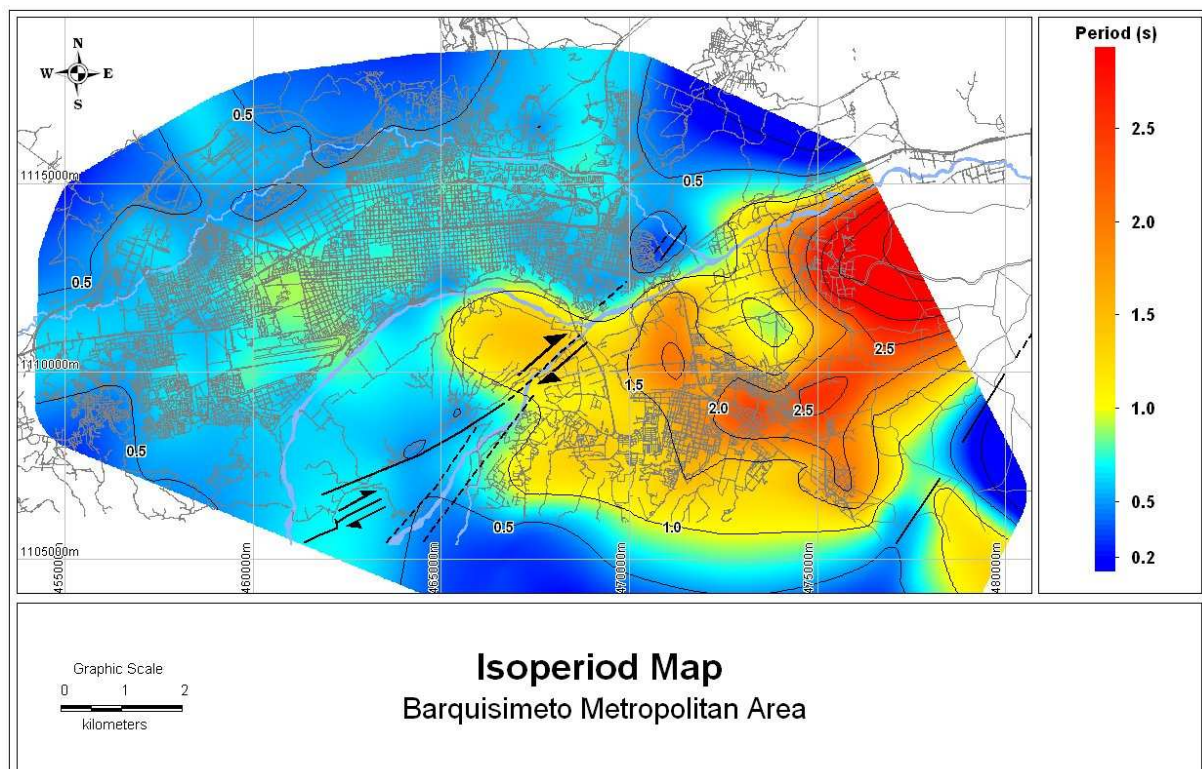


Figure 4. Isoperiod Map of the study area. The maximum values, over 2.5s, are observed in Cabudare, increasing towards NE.

From this result, it is possible to correlate the obtained values of periods with the sediment thickness, over Barquisimeto terrace and Cabudare basin (Figure 5). In Barquisimeto, the maximum depth is 120m in the southwest of the study area, while the average depth for the whole terrace is 80m. In the Cabudare pull-apart basin the maximum depth is 400m in the southeast, decreasing towards the edges. The ratio between the fundamental period and the sediment thickness used in this paper was taken from previous studies in Caracas (Rocabado et al., 2002), which include data of geotechnical drillings, water wells and seismic refraction profiles in order to determine the geometry and sediment thickness of Caracas basin, related with each single measurement of H/V.

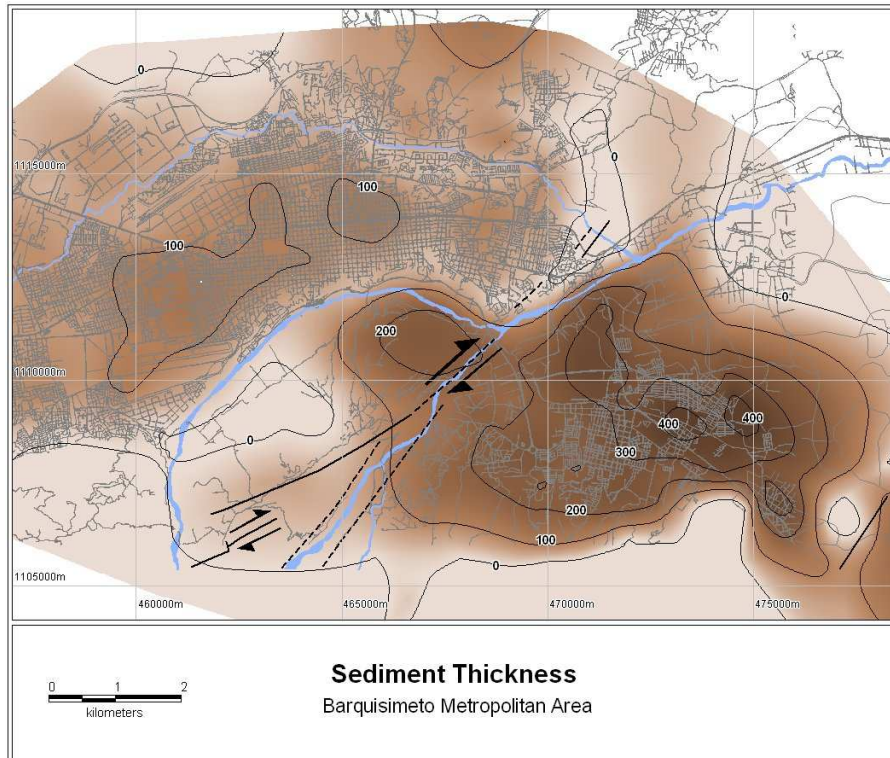


Figure 5. Sediment thickness estimated from H/V results; the maximum depth was 400m in the Cabudare pull-apart basin and 120m over the Barquisimeto terrace.

GRAVIMETRY MEASUREMENTS

A total of 620 single gravimetric measurements were done in Barquisimeto Metropolitan Area, with 500 m of distance between stations distributed in the study area (De Marco et al., 2004; Nobile, 2005) (Figure 6). The instrument used was a digital gravimeter SCINTREX CG3.

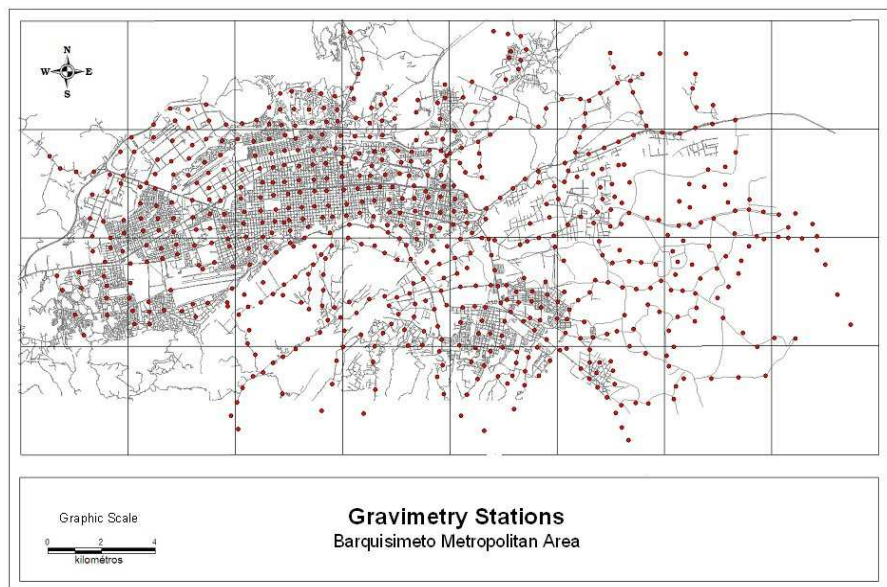


Figure 6. Grid of single gravity stations in the study area.

The target during data processing was to eliminate all the variables that could affect the gravity measurements like topography and instrumental derive. This was done in order to isolate lateral variations of density on subsoil materials that cause alterations in gravity values, from which the Bouguer Anomaly map is obtained (Figure 7).

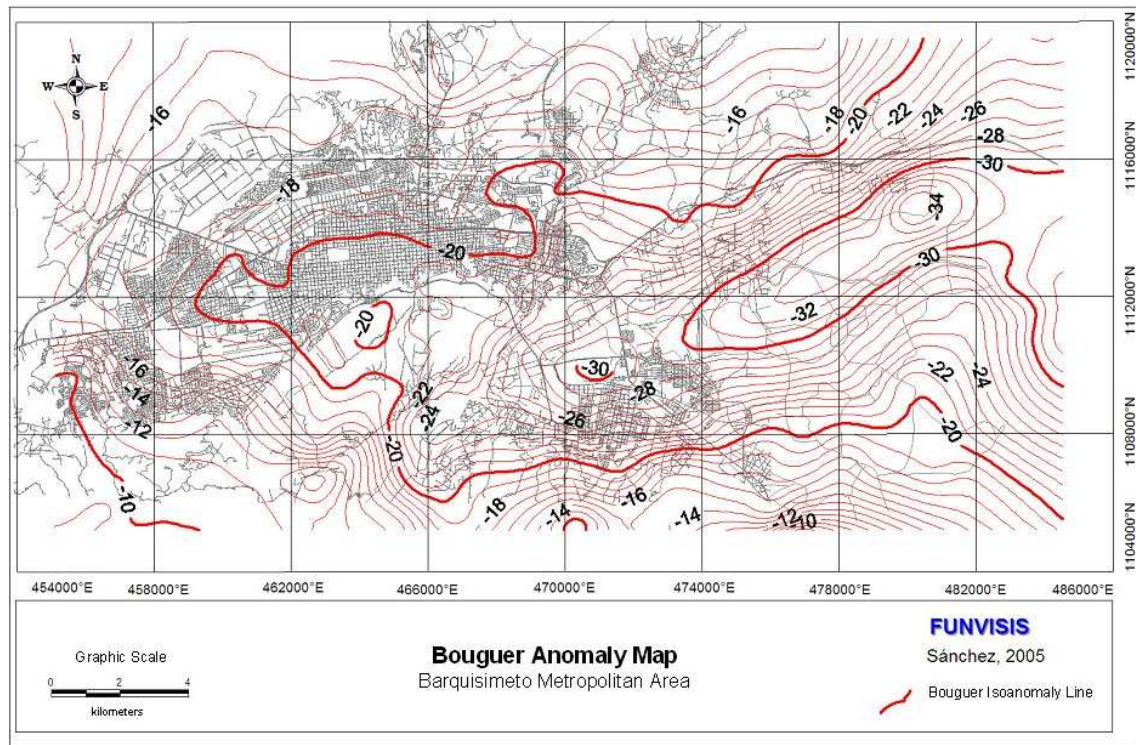


Figure 7. Bouguer Anomaly Map in the Barquisimeto Metropolitan Area.

A three-dimensional modelling was done using IGMAS software (Götze and Lahmeyer, 1988; Schmidt and Götze, 1998; Breunig et al., 2000). The 3D models were generated from bi-dimensional cross sections, starting with a simplified initial model obtained from geological information and few gravity points (De Marco et al., 2004; Bechtold, 2004). For modelling purposes, the 3D model was divided in parallel cross sections. Along the sections, the observed Bouguer Anomaly was compared with the response calculated along the section and the respecting geological units adjusted in 3D until a satisfactory fit was reached. For visualization, three cross sections were generated, two of them with NW-SE strike and in NE-SW direction (Figure 8). The thickness and location of sediments are controlled by data from 32 wells in the Barquisimeto Metropolitan Area; two of them (down to 100 and 300 m depth) were done by FUNVISIS, and will be instrumented with accelerometers in the bottom.

Based on the final 3D gravity model a map of sediment thickness was generated (Figure 8). The thickness estimated from seismic refraction profiles (De Marco *et al.*, 2004) was taken as constraint to the gravimetric model in Barquisimeto. Additional seismic refraction profiles are being done actually in Cabudare in order to constraint basement depth and seismic velocities of the sediments. For Barquisimeto, the sediments thickness varies between 0m and 300m, with the maximum values in the city center, decreasing toward to the north and south. In Cabudare, the bedrock depth varies between 0m and 600m, with an increase in sediment thickness in the direction of strike, towards NE, reaching a maximum of 750m. For both areas, the trend of the anomalies is consistent with the sediment thickness estimated from H/V (Figure 5). Nevertheless, the absolute values differ in the order of 1:2 between thickness from H/V (lower values) and gravimetric modelling (higher values). One possible explanation is that in the gravimetric model the upper meteorized part of the bedrock, might be included with the sediments. The results of the new seismic refraction lines (two of then adjacent to the deep boreholes) will hopefully help to clarify this discrepancy.

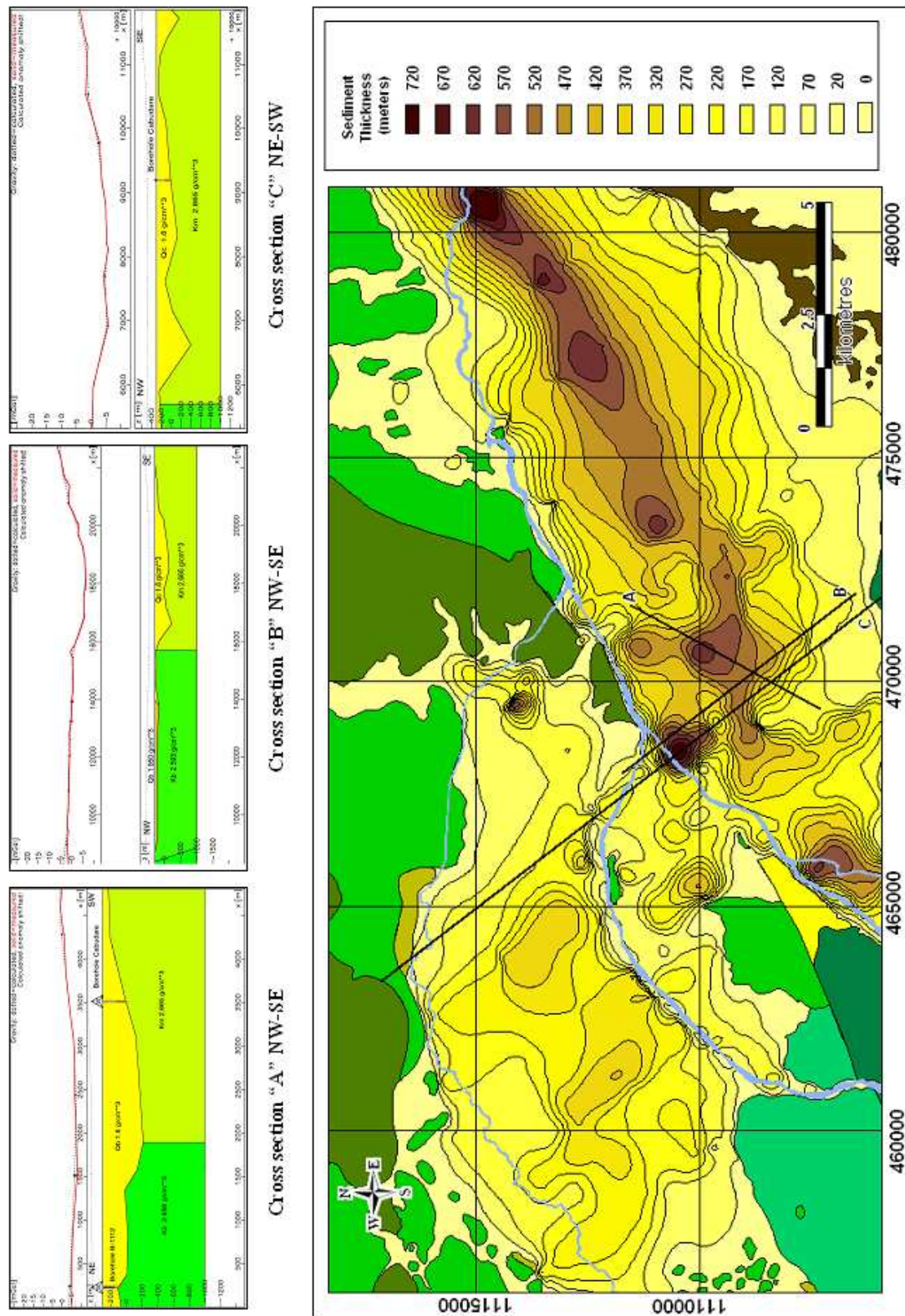


Figure 8. Sediment thickness obtained from 3D analysis of gravimetric data. Three 2D cross sections were included, showing the correlation of gravimetric response with geological formations.

CONCLUSIONS

From the results of H/V analysis it was possible to determine two regions with different response in Barquisimeto Metropolitan Area. First, in Barquisimeto city, a maximum values of 0.8s was observed in the west of the Quaternary terrace, whereas the minimum values are located to north of the city, corresponding to the foothill areas. Cabudare city shows the highest values of predominant periods with a maximum of 3.0s and an average of 1.5s in the remaining f area; the minimum values are located in the foothills towards the south.

Based on the gravity data, a Bouguer anomaly map was generated with values between -34 and -10 mGal; the minimum value is located in Cabudare. Corresponding values of sediment thickness, obtained from 3D gravity modelling, reach 300 m in Barquisimeto and more than 600 m in Cabudare. In general, there is a good agreement in the shape of both maps of sediment thickness (generated from H/V and Bouguer anomaly, respectively). Nevertheless, there are important differences in the absolute value of the sediment thickness, with a maximum of 120 and 300 m in Barquisimeto and of 500 and 750 m in Cabudare, derived from analysis of H/V and gravity data, respectively. The seismic refraction profiles, actually being measured in Cabudare, will help to adjust the sediment thickness in this area. Using this information, a proper relation between predominant periods and sediment thickness will be established for Barquisimeto Metropolitan Area, which might help to adjust the map of sediment thickness using H/V data.

The data obtained in this study will be used to determine microzones with similar seismic response within Barquisimeto Metropolitan Area. The definition of the microzones will be based on the cartography of the principal geological and geomorphologic units, together with the sediment thickness (discussed in this paper) and seismic velocities (V_{s30}). Typified spectra will be associated to the corresponding microzones in order to determine the boundaries between them, and the respective seismic response. Recommendations regarding general building characteristics, considering the seismic response in each microzone, will be given to local authorities and communities.

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REFERENCES

- Abeki, N., Watanabe, D., Hernández, A., Pernía, A., Schmitz, M. and Avendaño, J., 1998a. Microtremor observations in Cumaná city, Venezuela. In: Irikura et al. (eds.), *The Effects of Surface Geology on Seismic Motion*, Balkema, Rotterdam, 613-618.
- Abeki, N., Seo, K., Matsuda, I., Enomoto, T., Watanabe, D., Schmitz, M., Rendón, H. and Sánchez, A., 1998b. Microtremor observations in Caracas city, Venezuela. In: Irikura et al. (eds.), *The Effects of Surface Geology on Seismic Motion*, Balkema, Rotterdam, 619-624.
- Bard, P.Y., 1999. Microtremor measurements: a tool for site effect estimation? In: Irikura, K., Kudo, K., Okada, H. and Sasatani, T. (eds.), *The Effects of Surface Geology on Seismic Motion - Recent progress and new Horizon on ESG Study*, Volume III, Balkema, Rotterdam, 1251-1279.
- Bard, P.-Y. and SESAME participants, 2005. From ambient noise measurements to site effect assessment: main results from the SESAME project. IV Coloquio sobre Microzonificación Sísmica, Barquisimeto, noviembre 2005, Serie Técnica FUNVISIS No. 1, 2005, 36-57.
- Bechtold, M., 2004, Mapa geológico digital de Barquisimeto y alrededores con énfasis cuaternario. Unpublished report, FUNVISIS, Caracas.

- Breunig, M., Cremers, A.B., Götze, H.-J., Schmidt, S., Seidemann, R., Shumilov, S. & Siehl, A., 2000: Geological Mapping based on 3D models using an Interoperable GIS. *Geo-Information-Systems, Journal for Spatial Information and Decision Making*, ISSN 0935-1523, 13, 12 - 18.
- De Marco, R., Bechtold, M., Audemard, F., Sánchez, J., Rocabado, V., Schmitz, M., 2004. Caracterización geofísica/geológica de la terraza de Barquisimeto, estado Lara: Integración de Ruido Sísmico Ambiental, Sísmica de Refracción, Gravimetría y Geología. XVIII Seminario de Geotecnia, Caracas, CD, 12 pp.
- Enomoto, T., Schmitz, M., Matsuda, I., Abeki, N., Masaki, K., Navarro, M., Rocabado, V. and Sanchaz, A., 2000. Seismic risk assessment using soil dynamic characteristics in Caracas, Venezuela. 6th International Conference on Seismic Zonation, Palm Springs, Nov. 12-15, 2000, CD-ROM, 6pp.
- Field, E.H. and Jacob, K.H., 1995. A comparison and test of various site-response estimation techniques, including three that are not reference-site dependent. *BSSA*, 85, 1127-1143.
- González, J., Schmitz, M., Audemard, F., Masaki, K., Contreras, R., Mocquet, A., Delgado, J. and De Santis, F., 2004. Site and induced effects associated with the 1997 Cariaco earthquake. *Engineering Geology*, 72, 143-177.
- Götze, H. J. y B. Lahmeyer. 1988. Aplicación de three-dimensional interactive modeling in gravity and magnetics. *Geophysics*, 53 (8): 1096-1108.
- Grases J, 1990. Terremotos destructores del Caribe 1502 – 1990. 1ª Ed. ORCYT – UNESCO, Montevideo, Uruguay, 132 pp.
- Hernández, J.J., Schmitz, M., Audemard, F., 2006. Marco conceptual del proyecto de microzonificación de Caracas y Barquisimeto. VIII Congreso Venezolano de Sismología e Ingeniería Sísmica, Valencia, 2006, Memorias en CD, 8 pp
- Ibs-von Seht, M. and Wohlenberg, J., 1999. Microtremor measurements used to map thickness of soft sediments. *BSSA*, 89, 250-259.
- Konno, K. and Ohmachi, T., 1998. Ground motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor. *BSSA*, 88, 228-241.
- Lachet, C. and Bard, P.-Y., 1994. Numerical and theoretical investigations on the possibilities and limitations of Nakamura's technique. *J. Phys. Earth*, 42, 377-397.
- Moros, L. 2005. Relación entre el período fundamental de vibración del suelo y el espesor de sedimentos en el Este de la ciudad de Caracas, mediante la aplicación del método de Nakamura a datos obtenidos en una malla de mediciones de 250 metros. Undergraduate thesis. Universidad Central de Venezuela.
- Moreno, F. 2005. Relación entre el Período Fundamental de vibración de suelo y el espesor de sedimentos en la parte oeste de la ciudad de Caracas, Municipio Libertador, mediante la aplicación del método de Nakamura en una malla de 250 metros. Undergraduate thesis. Universidad Central de Venezuela.
- Nakamura Y., 1989. A Method for Dynamic Characteristics Estimation of Surface using Microtremor on the Ground Surface. *QR of RTRI*, Vol 30, No 1.
- Nobile, J. 2005. Caracterización Geofísica de la Cuenca Pull-Spart de Cabudare, Noroccidente de Venezuela. Undergraduate thesis. Universidad Simón Bolívar.
- Nogoshi, M. and Igarashi, T., 1971. On the amplitude characteristics of microtremor (part 2). *Jour. Seism. Soc. Japan*, 24, 26-40 (In Japanese with abstract in English).
- Palme, C., Choy, J., Guada, C. y Morandi, M., 2002. Mediciones de vibración ambiental en la ciudad de Ejido, estado Mérida, Venezuela. . III Coloquio sobre Microzonificación Sísmica, Caracas, 15 al 18 de Julio 2002, Memorias, Serie Técnica No. 1-2002, FUNVISIS, Caracas, 81-85.
- Parolai, S., Bormann, P. and Milkereit, C., 2001. Assessment of the natural frequency of the sedimentary cover in the Cologne area (Germany) using noise measurements. *J. of Earthquake Engineering*, 5, 541-564.
- Parolai, S., Bormann, P. and Milkereit, C., 2002. New relationships between Vs, thickness of sediments, and resonance frequency calculated by the H/V ratio of seismic noise for the Cologne area (Germany). *BSSA Short Note*, Vol. 92, 2521-2527.
- Rocabado, V., Schmitz, M., Malavé, G. y Enomoto, T., 2001. Períodos fundamentales y amplificación del suelo de la ciudad de Caracas utilizando la técnica de Nakamura. *International Workshop*

- “Study on Countermeasures for Earthquake Disaster in Caracas (1999 – 2001)”, Caracas, Venezuela, August 24 - August 25, 2000, Série Técnica, FUNVISIS, Caracas, 130-139
- Rocabado, V., Schmitz, M., González, J., Andrade, L., Vilorio, A., Enomoto, T., Abeki, N., Delgado, J., 2002. Seismic microzoning study in Barquisimeto, Venezuela. 12th European Conference on Earthquake Engineering, London, 9 – 13 September 2002. Extended abstract. 7 pp.
- Romero, M., Cragno, A., Ambrosio, R., Schmitz, M. y González, J., 2006. Evaluación geofísica de los conos aluviales en Macuto, Caraballeda y Tanaguarena, Edo. Vargas. Boletín del IMME, 44 (1), 16-29.
- Schmidt, S. and H.-J. Götze, 1998: Interactive visualization and modification of 3D models using GIS functions. *Physics and Chemistry of the Earth*, 23 (3), 289-295.
- Schmitz, M. Hernández, J.J., Tagliaferro, M., Hernández, A., González, M., Rocabado, V., Cornou, C., Sánchez, J., Amaris, E., Cano, V., Singer, A., Feliziani, P., 2007. Determinación de microzonas de igual respuesta sísmica en Caracas. IV Congreso Cubano de Geofísica, Simposio de Sismología y Riesgo Sísmico, La Habana, Cuba, Marzo 2007, abstract.
- Semblat, J.F., Duval, A.M. and Dangla, P., 2002. Seismic site effects in a deep alluvial basin: numerical analysis by the boundary element method. *Computers and Geotechnics*, 29, 573-585.