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Seismic Zonation of Barcelona Based on Numerical Simulation of Site Effects

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Abstract—Seismic responses of different sites of Barcelona have been investigated through numerical modelling. Geological maps and geotechnical data available from drillings for buildings and infrastructures have been used to determine the dynamical properties of the soils through different correlations between standard geotechnical data and dynamical parameters obtained in other regions. An estimation of the depth of the Palaeozoic basement has been obtained through an inversion of a detailed gravity survey. A 1-D equivalent linear method has been used to compute complete transfer functions and other spectral responses, such as PSA and PSV for various damping values, with the purpose of classifying zones with similar behaviour. Given the uncertainties associated with the input data, a Montecarlo's simulation process has been carried out. Four zones, characterized by their corresponding transfer function and by PGA amplifications, are proposed. The numerical results are compared with those previously obtained through microtremor measurements, showing that predominant periods derived from Nakamura's technique should be taken carefully.

Key words: Site effects, numerical simulation, Nakamura technique, microzonation.

Introduction

The city of Barcelona is located NE of the Iberian Peninsula (see Fig. 1). This area is considered to be of a moderate seismic activity and it is classified with an intensity VI MSK for a return period of 500 years by the Spanish Seismic Code (NCSE-94, 1995). Recent studies (Secanell, 1999; Goula *et al.*, 1998a) assess this intensity as VI–VII MSK for tertiary materials cropping out in the town. Some factors, such as the high population density, buildings with a high vulnerability index, and the presence of a Pleistocene-Holocene Quaternary cover, on most of the dwellings are founded, can produce considerable amplification of the seismic effects. It is therefore of great interest to investigate the seismic response of the different soil

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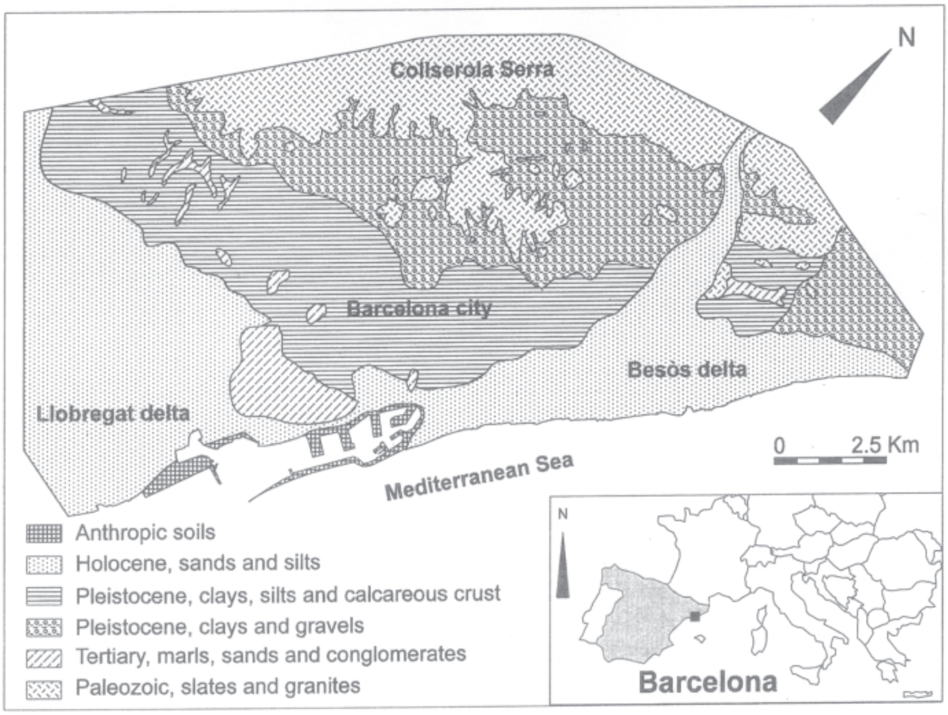

Figure 1
Geological map of the studied zone, modified from LOSAN (1978).

conditions, assessing the amplification characteristics of the ground motion that can take place in future earthquakes for the different zones.

Several studies have been recently carried out: a preliminary study of microzonation with the evaluation of five transfer functions, based on 1-D methods (FIGUERAS *et al.*, 1995); a methodological study which allows the estimation of the soil dynamic parameters (CID, 1996); creation and exploitation of a geotechnical data base and a seismic zonation based on numerical simulation of site effects (CID, 1998); a study of the sensitivity of the geotechnical parameters in the simulation of the local seismic effects (BARCHIESI *et al.*, 1997); an application of the NAKAMURA's (1989) method measuring microtremors as a tool to obtain the predominant periods (ALFARO, 1997; ALFARO *et al.*, 1997); a comparison of the results obtained in a numerical simulation with those resulting from the Nakamura's method (GOULA *et al.*, 1998b) and with gravimetric data (SUSAGNA *et al.*, 1998); and, finally, a first application of an integrated GIS environment to mapping soil effects (JIMÉNEZ *et al.*, 2000).

This paper presents a synthesis of the different results obtained, with the aim of defining a seismic zonation of the city of Barcelona, based on the complete soil transfer functions. Most of the studies to obtain these results have been carried out within the European projects Euro-Seistest and Euro-Seismod (http://euroseis.civil.auth.gr), which were devoted to the development and calibration of experimental and numerical methods for characterising soil effects through specific applications.

The main results presented in this paper have served for preparing the emergency plans of the City Council of Barcelona, and, in particular, the characteristics defined for each of the seismic zones have been incorporated into the civil defence plans for the City of Barcelona (AMIEIRO and CID, 1999).

Geological Situation and Geotechnical Data

Figure 1 shows a geological map of the city of Barcelona, which is located on the plain of the pediment of the *Serra de Collserola* which is part of the *Catalan Coastal Range*. Its general orientation is parallel to the coastline and its boundaries are the *Besòs* Delta at the NE and the *Llobregat* Delta at the SW.

Two geomorphological units can be distinguished: the mountainous relief which constitutes the town substrate (where we can find metamorphic and granitic Palaeozoic materials and Tertiary materials) and the Barcelona plain, itself divided into two geomorphological units: the town centre formed by Pleistocene materials and the deltaic deposits of the *Besòs* and *Llobregat* rivers, formed by Holocene materials.

The Palaeozoic materials (Ordovician-Carboniferous) are mainly composed of materials of sedimentary origin, affected by different degrees of metamorphism and by plutonic materials (granites), quite often superficially altered, known under the name of *sauló*. The Tertiary materials are discordantly placed over the above described materials. Amongst them we can distinguish the materials formed by a strong marine series, from shallow waters, with alternated layers of bluish, fossilipherous marls, reddish-grey sandstones and levels of micro-conglomerates from the Miocene, and the materials from the Pliocene, consisting of a lower layer of bluish-green marls with numerous fossils and a higher layer with sandy marls and dark yellow sands (LOSAN, 1978).

Quaternary materials can be differentiated by their age, Pleistocene or Holocene. The Pleistocene materials, locally known as *Tricicle* are discordantly located over a rocky substrate which can be any one of the above described materials, depending upon the sector. Generally speaking, the thickness of these materials is very variable, oscillating between 18 and 25 metres, with increasing thickness towards the coastal line. They are basically formed by red compact clays, yellowish silts of eolic origin and limestone crusts 20–30 cm thick. The Holocene materials correspond to the deltaic deposits of the *Besòs* and *Llobregat* rivers, basically formed by coarse sand and gravel, silts and intermediate clays, fine or coarse sand, brown plastic silts and humus soil. These materials lay over Palaeozoic or Pliocene substrate in the case of the *Besòs* and over Pliocene in the case of the *Llobregat*. The thickness of the Holocene materials is also variable, reaching almost 100 metres in the *Llobregat* and about 50 metres in the *Besòs*, both decreasing towards the margins of the deltas.

A first step, within the seismic microzonation studies of the City of Barcelona, was the compilation of as much geotechnical information as possible on the subsoil of the town. An interactive geotechnical data base, GeotHDS 2.00, was designed with the aim of being a useful tool in the process of assessing seismic risk (CID, 1998). All geotechnical parameters found in each one of the available geotechnical reports have been introduced. The basic unit is an individual drilling.

The different subprojects which are necessary phases of a whole seismic microzonation programme often constitute themselves very interesting and useful issues. This is the case of the task of compiling geotechnical data which is of great interest for urban planning. It is worthwhile mentioning that in the case of Barcelona the objective of seismic microzoning was the start of an independent project for the elaboration of a new geotechnical map which was published in CD-ROM (ICC, 2000).

Seventy geotechnical representative columns were selected for this seismic microzonation study. Figure 2 shows its location on the map.

Estimation of the Soil Dynamic Parameters

Several soil dynamic parameters are needed to simulate, numerically, the effect produced by these soils in the propagation of seismic waves; shear-wave velocity (V_s), maximum dynamic shear modulus (G_{max}), density (ρ) and layer thickness. A methodology was defined (CID, 1996) which allowed the estimation of the soil dynamic parameters starting from geotechnical parameters, commonly used in civil works. This solved the problem of the lack of experimental values for the dynamic properties of the Barcelona soils.

The results obtained from Standard Penetration Test (Nspt-values) are correlated empirically with the shear-wave velocity in each layer, using a series of empirical correlations (CID, 1998) proposed by different authors (BORCHERDT, 1994; IAI *et al.*, 1995; PECKER, 1995; DICKENSON and SEED, 1996; PITILAKIS, personal communication).

From the application of these correlations a non-negligible scatter results, still increased by the consideration of uncertainties on the Nspt-values and a correction factor of 1.25 for velocities on Pleistocene materials (PRESTI and LAI, 1989). One example of the obtained results is shown in Figure 3 for a representative column of the Llobregat Delta (site 5 in Fig. 2), where 96 values of shear velocity are obtained for the layer no. 4, with an average value of 250 m/s and a standard deviation of 27 m/s (CID, 1998).

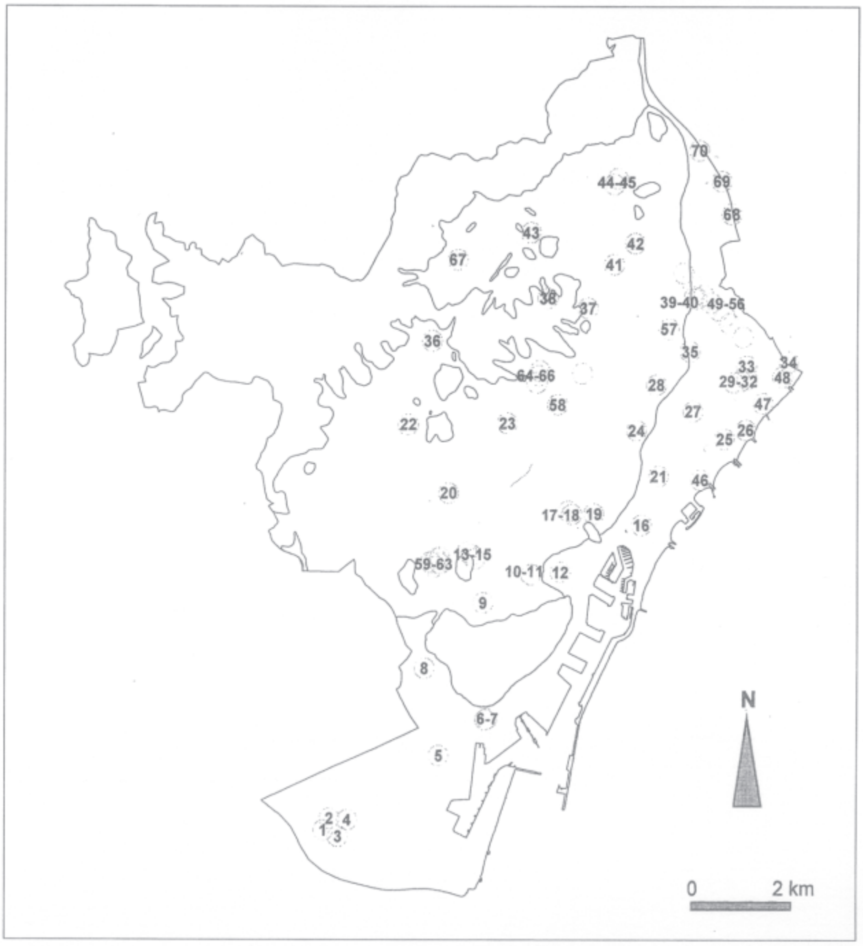

Figure 2
Location of the representative columns on the different geological units described in Figure 1.

The parameters of 70 columns, with depths of around 15 metres, have been estimated. The location of these columns are shown on the map of Figure 2. Close to the foothills, the Palaeozoic basement is found at a depth less than 20 metres. As we approach the coastal line, we find the presence of Tertiary materials; the lack of geotechnical surveys reaching these depths make it difficult to define the Tertiary-Palaeozoic contact. For this reason we have resorted to the preliminary results from inversion of detailed gravimetric data (LÁZARO *et al.*, 1998), which allows a preliminary estimation of the depth of this Tertiary-Palaeozoic contact.

Figure 4 indicates the values of shear-wave velocity for the soil columns of the 70 locations. In these columns we can find schematically from bottom to top: Palaeozoic materials with a shear velocity of 2000 m/s and with a maximum depth, in some

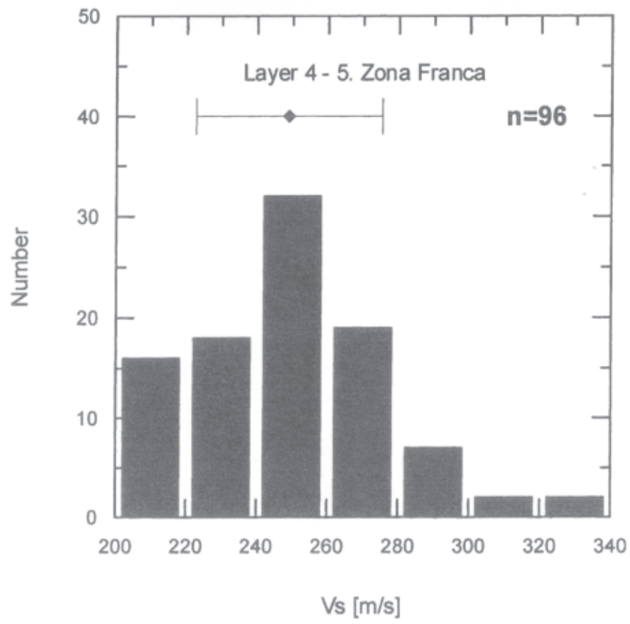

Figure 3
Distribution of the 96 obtained values of V_s by applying the different correlations used with consideration of uncertainties and corrections, for layer no. 4 of a representative site of the Llobregat Delta (no. 5 Zona Franca). The average value of 250 m/s and standard deviation of 27 m/s are also shown in the figure.

points, exceeding 300 m; Tertiary materials with a shear-wave velocity of 1200 m/s, absent in the upper part of the town, and with a thickness which increases towards the coastal line reaching, at some points, 300 m; Quaternary materials, which can be Pleistocene, with a shear velocity under 400 m/s, with a thickness of under 20 m, located in the central-high area of the town, or Holocene with lower shear velocities, with a maximum thickness of 70 m, located in the deltaic materials of the *Llobregat* river.

Numerical Simulation of the Site Effects

For the numerical simulation of the local seismic effects in the different points under study, a selection of input motions are required. As is a common practice in many other studies using numerical simulation (Bard and Bouchon, 1980a, b; Jongmans and Campillo, 1993; Chávez-García and Bard, 1994; Riepl, 1997), the input motions have been defined as a series of Ricker pulses with predominant frequencies 2–7 Hz. In Figure 5 one of these input signals is presented together with its corresponding spectra (PSA) which shows a frequential content quite similar to the one proposed in seismic regulations.

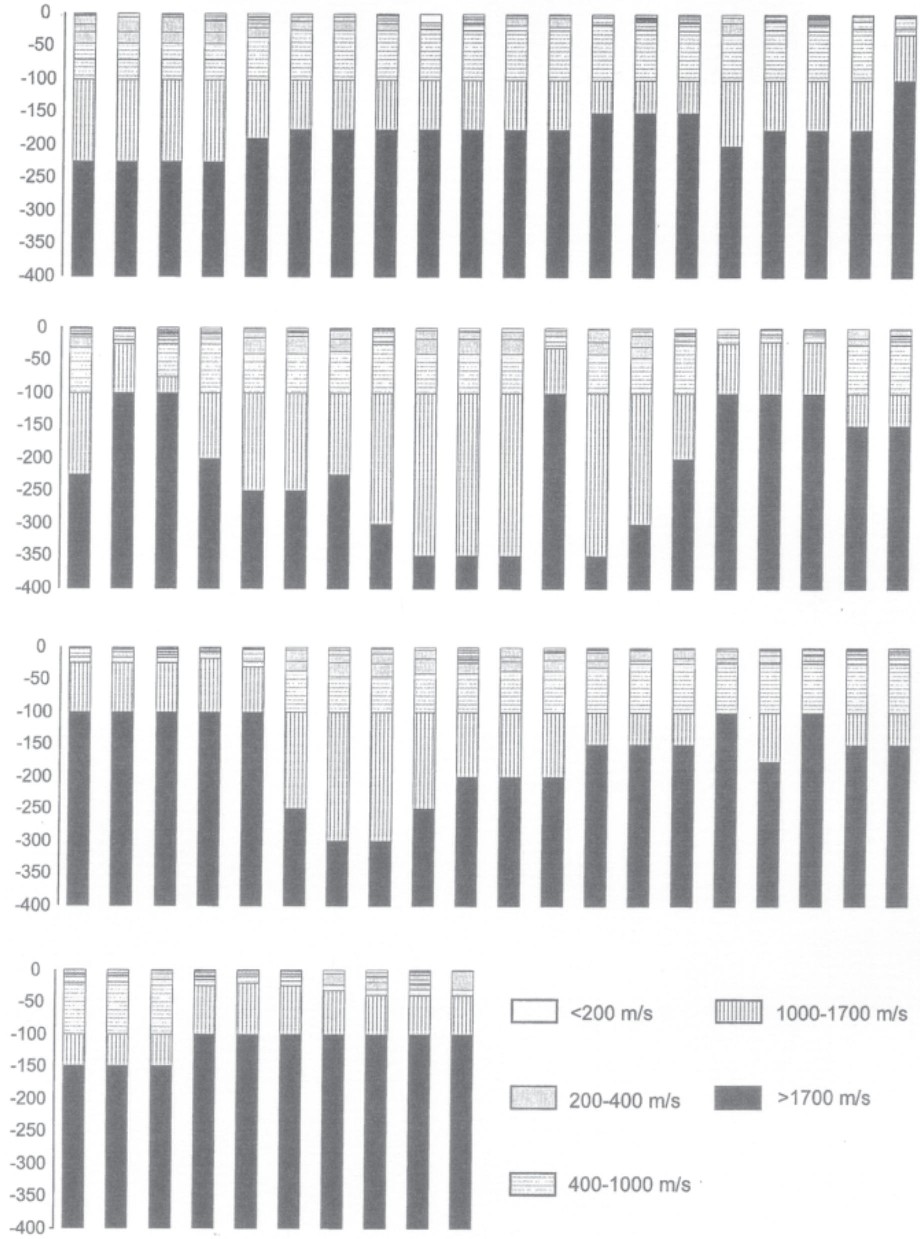

Figure 4
Synthetic representation of the different V_s obtained down to the Palaeozoic basement for 70 columns. The columns are arranged from left to right and from top to bottom according to their location number in Figure 2.

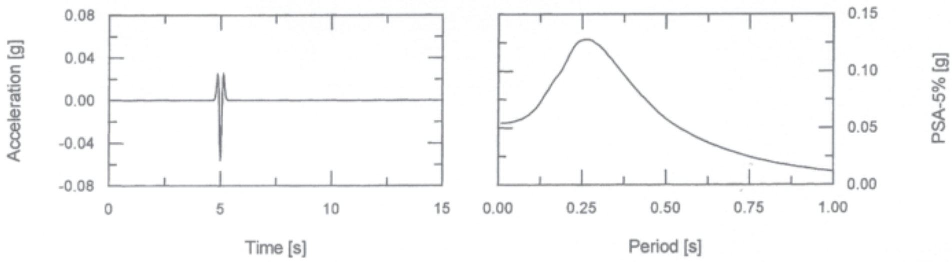

Figure 5
Input signal, with a predominant frequency of 3 Hz, represented temporally (accelerogram) and frequentially (response spectrum).

In our case the maximum acceleration level of these signals has been defined according to recent studies of seismic hazard (SECANELL, 1998; GOULA *et al.*, 1998a), which obtained an intensity VI–VII MSK for a return period of 500 years in the Tertiary materials of the town of Barcelona. This corresponds to a value of the peak ground acceleration of 0.054 g (Fig. 5) according to the relation proposed in the Spanish Seismic Code (NCSE-94, 1995).

Once the one-dimensional models of the subsoil for the studied points and the acceleration level of the input motion are defined, then a 1-D linear-equivalent method, Shake'91 (IDRISS and SUN, 1992) is applied. Given the geometry and the soil properties of the study area and the level of the input motion, a 1-D linear-equivalent method appears to be a good approach.

Figure 6 shows, for different types of materials, the variation of the dynamic shear modulus (G) normalised to the maximum dynamic shear modulus ($G_{\max}$) and of the damping ratio (D) against the shear deformation, that will be used for the calculations. These variation curves are taken from the recent experimental data obtained in the Volvi valley (AUTH.SF, 1997), selecting the more appropriate to the local conditions of Barcelona.

These input data have been defined for a reference basement, i.e., Tertiary outcrops in Barcelona. Therefore, these signals should be deconvoluted to the Palaeozoic basement (considered as outcropping). The dynamic model (average values and uncertainties) used for this deconvolution is shown in Table 1. Dynamical parameters of the reference site have been estimated for an assumed representative column of outcropping Tertiary materials in Barcelona. Average values and uncertainties have been considered in order to compute the transfer function relative to the Palaeozoic basement and its sensitivity to uncertainties by a Montecarlo process with a different number of computations. Figure 7 shows the average computed transfer function for 10, 100, 200, 500 and 1000 simulations. It is seen that stability is reached at 500 computations.

The deconvoluted signals have been introduced at the base of each soil column (Fig. 4). As the number of analysed sites is not very large (70 points) with regard to

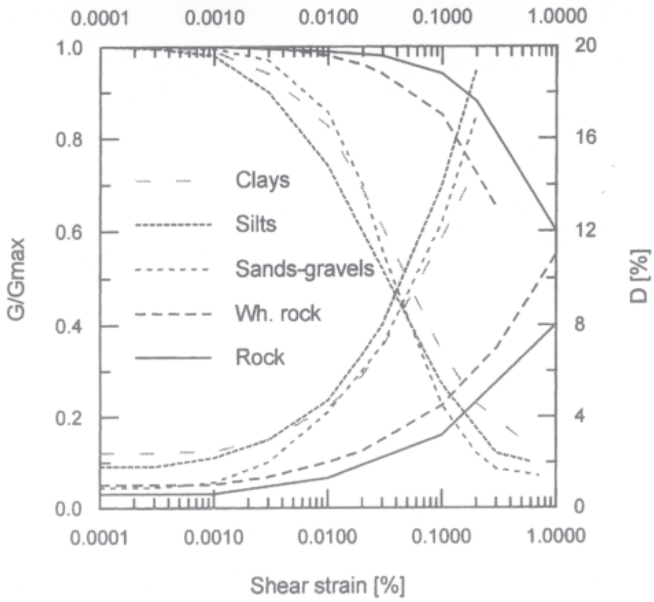

Figure 6
Modulus reduction (G) and damping curves (D) with shear strain amplitude used in the linear-equivalent method (from AUTH SF, 1997).

the extension of the area under study, in order to carry out the seismic zonation of the city the following functions have been calculated for each site:

1. Signal (acceleration time story) on the surface.
2. Transfer function between the surface and the Palaeozoic basement (considered as outcropping).
3. Pseudo-acceleration elastic response spectrum for a damping of 5%.
4. Pseudo-acceleration elastic response spectrum for a damping of 5%, normalised to the peak ground acceleration.
5. Pseudo-velocity elastic response spectrum for a damping of 5%.

In order to analyse the degree of uncertainty of each one of these functions, a Monte-Carlo's simulation process has been applied (500 computations), varying the values of V_s for the uppermost layers, according to what has been described above (see example in Fig. 3). The standard deviation has been assumed to be 15% of the average value for deeper thickness, 10% for deeper V_s and 0.2 g/cm^3 for the density.

One example of the obtained results is shown in Figure 8, where the average transfer function for site no.5 (located on the Llobregat Delta) is shown together with one- and two- standard deviation curves, corresponding to 500 computations.

All five above-mentioned functions were computed, considering six different input signals (above described) at the 70 sites and using a Monte-Carlo's simulation

Table 1

Dynamic parameters of the reference site for the town of Barcelona, average values with this corresponding standard deviations

Type	Average thickness [m]	σ [m]	Average density [g/cm^3]	σ [g/cm^3]	Average V_s [m/s]	σ [m/s]
Altered Rock	10	4	2.3	0.2	550	55
Rock	90	13.5	2.4	0.2	900	90
Rock	75	11.25	2.6	0.2	1200	120
Rock	75		2.6	0.2	2000	200

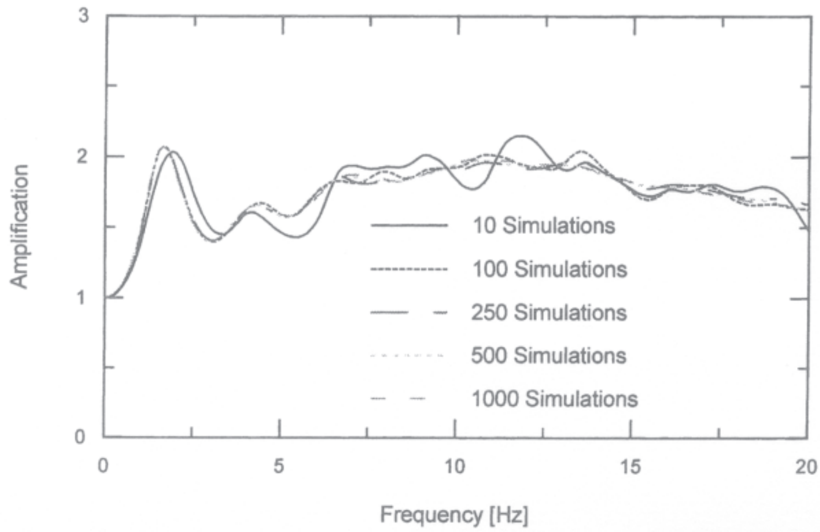

Figure 7
Transfer function of the reference site (Tertiary outcrop) relative to Palaeozoic basement (considered as outcropping) obtained though a Monte-Carlo's simulation process with different numbers of computations.

process with 500 computations in order to take into account the uncertainties of the dynamical parameters (CID, 1998).

Seismic Zonation

The simulated functions have been classified, taking into account analogies, arriving finally to group the 70 sites in three classes. As an example, Figure 9 shows the transfer functions between the surface and Palaeozoic basement (considered as outcropping) grouped in the three soil zones finally obtained.

The set of sites defined for each zone corresponds roughly to the geological units defined in Figure 1, i.e.: Zone I: Holocene outcrops, corresponding to Llobregat and

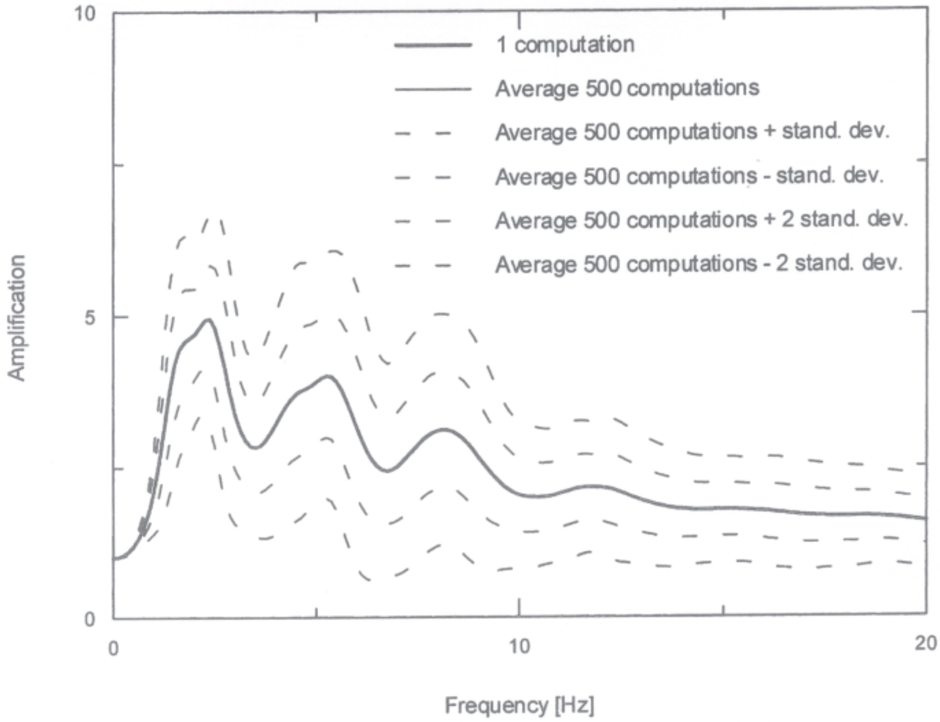

Figure 8
Average transfer function for site no. 5 (on Llobregat Delta) together with one- and two-standard deviations curves obtained from a Monte-Carlo's simulation process with 500 computations.

Besos Deltas. Zone II: Pleistocene outcrops with Tertiary substrate with sufficient thickness to have an influence on the soil amplification and Zone III: Pleistocene outcrops without Tertiary substrate with sufficient thickness to have an influence on the response. Adding a Zone 0, corresponding to rock outcrops (Palaeozoic and Tertiary) a final zonation map is presented in Figure 10.

Each zone is characterized by a transfer function and by an amplification factor for the peak ground acceleration level (PGA) relative to a reference site (outcropping Tertiary material). The average transfer functions together with one-standard deviation curves are shown in Figure 11. A synthesis of the main values obtained are also shown in Table 2.

Discussion

Given the uncertainties associated with the estimated values of the soil parameters, a sensitivity analysis through a Monte-Carlo's simulation process has been carried out. For a same site a set of resulting functions is obtained, leading to

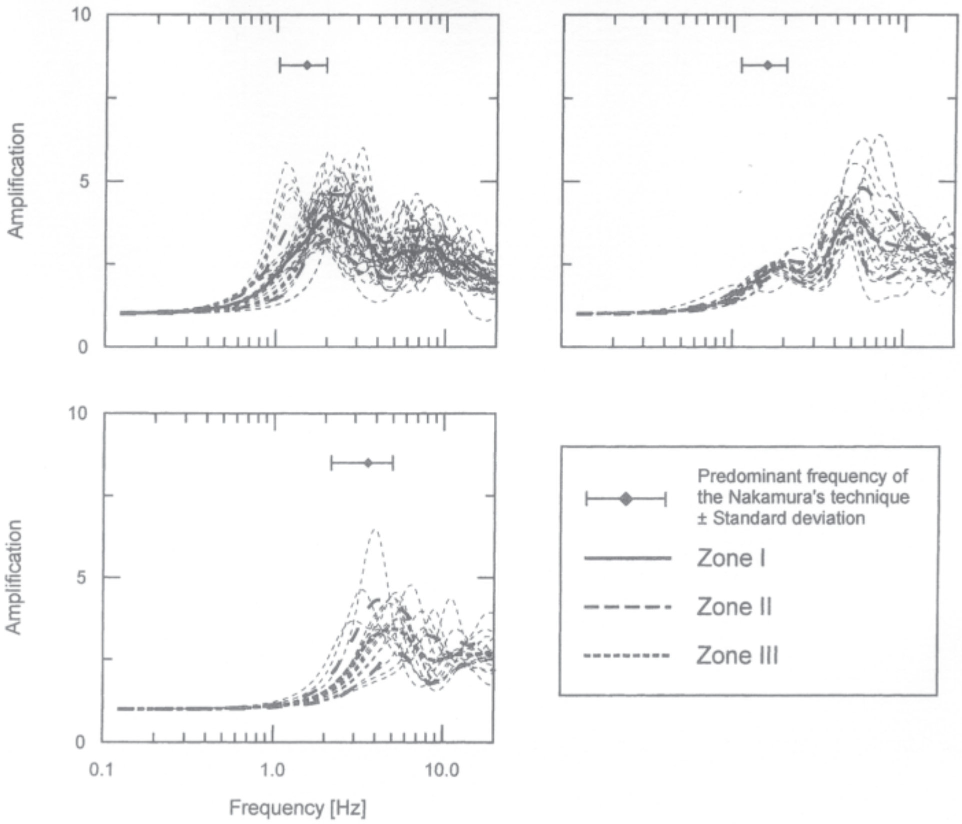

Figure 9
Classification of the transfer functions between the surface and the Paleozoic basement (considered as outcropping), on three zones, with their averages and one-standard deviation curves. The average and one-standard deviation values of predominant frequencies obtained through experimental microtremor campaigns analysed by Nakamura's technique (ALFARO *et al.*, 1997, 2000) computations for the same zones are also shown.

significant dispersion. That means that the interpretation of the individual results for each soil column may be considered prudently, and this is the reason for preferring to present final results as smoothing curves representative of a large area rather than as individual ones representing a small area. For a detailed microzonation, it would be necessary to have a better, detailed knowledge of the dynamical properties of soils, not available to date for Barcelona. This is also the reason why the smoothed amplification values presented in this paper are lower than the individual values obtained by JIMÉNEZ *et al.* (2000). Moreover, in this last mentioned paper, amplifications were computed by a similar method taking as reference site the Palaeozoic basement, thus obtaining larger amplifications than in the present study in which the reference site is the Tertiary basement.

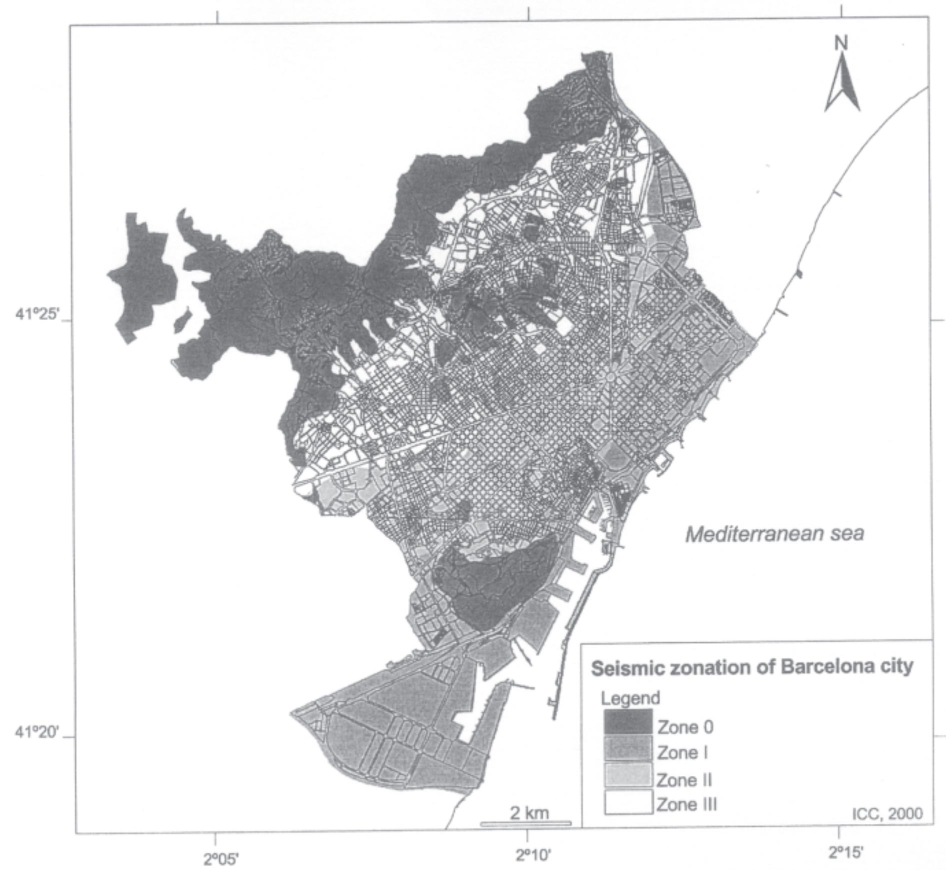

Figure 10
Seismic zonation of the town of Barcelona based on numerical simulation of the local effects. The four zones have been identified by the analysis of different simulated functions corresponding roughly to the main geological units of the geological map presented in Figure 1.

In order to compare numerical simulations with microtremor measurements (JIMÉNEZ *et al.*, 2000) it is better to analyse complete transfer functions as will be seen in the following discussion.

The transfer functions for the three classified zones, with respect to the Palaeozoic basement are presented in Figure 9, together with the average value of the predominant frequency obtained from microtremor measurements using Nakamura's technique (ALFARO, 1997; ALFARO *et al.*, 2001). From the analysis of this figure the next considerations can be pointed out:

Zone I is characterised by outcrops of Holocene deltaic materials with an average shear-wave velocity of approximately 200 m/s for the first metres (around 20 metres). Schematically, the subsoil column can be represented by a layer of Quaternary

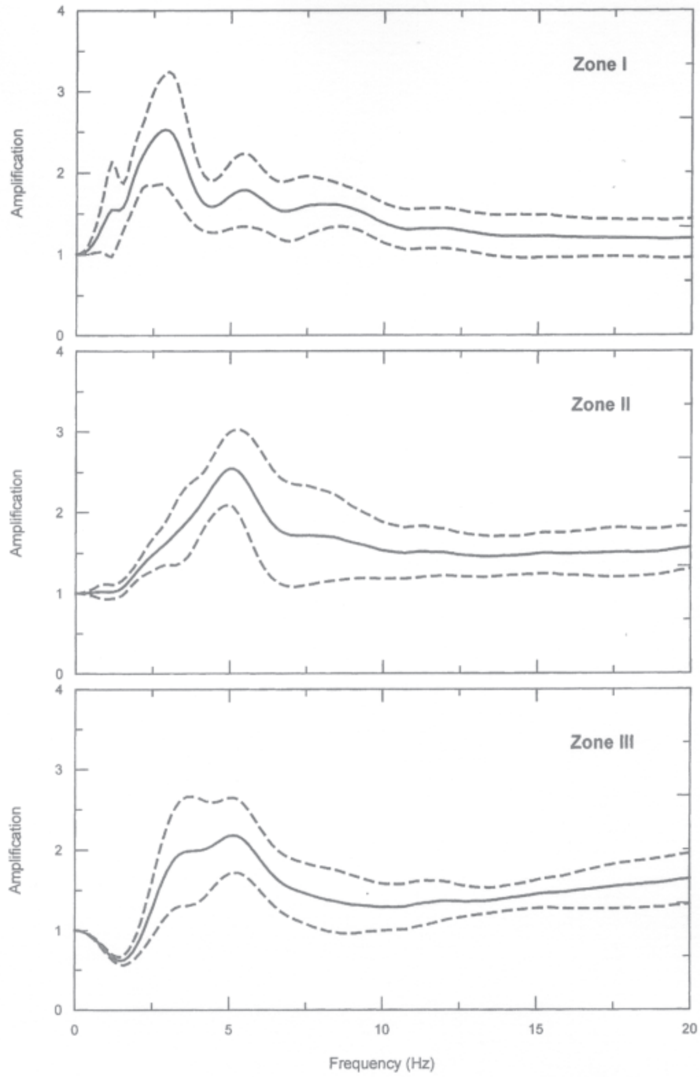

Figure 11
Transfer functions (R.S.R) characterizing the four zones with their average and one-standard deviation. Zone 0 is characterised by a flat transfer function; Zone I shows a maximum amplification value close to 2.5 Hz, with a maximum amplification of around 2.5; Zone II shows a maximum amplification value close to 5 Hz, with a maximum amplification of around 2.5; Zone III shows a maximum amplification value close to 5 Hz, with a maximum amplification of around 2.25 and with a de-amplification of the low frequencies.

materials with thickness ranging from 25–70 metres, on top of another very thick layer of Tertiary materials. Under these layers we find the Palaeozoic basement, at depths of less than 350 m. The transfer function is characterised by a first peak

Table 2

Average values of peak ground acceleration amplification, frequency of maximum amplification and maximum amplification factor for the four zones in Figure 10

Zone	PGA amplification	Frequency of maximum amplification (Hz)	Maximum amplification factor
0	1	–	–
I	1.69	2.5	2.5
II	1.65	5	2.5
III	1.43	5	2.25

located in the range of 0.8–2 Hz and a maximum amplification peak in the range of 1.5–2 Hz. The maximum amplification value ranges between 3 and 6, reflecting a high attenuation for higher frequencies. The predominant frequency of Nakamura's technique displays values ranging between 0.8 and 2 Hz.

Zone II is characterised by outcrops of Pleistocene materials with an average shear-wave velocity of around 300 m/s for the first metres (around 20 metres). Schematically, the subsoil column can be represented by a layer of Quaternary materials with thickness ranging from 10–25 metres on top of another layer of Tertiary materials reaching a depth of 100–350 metres, where the Palaeozoic basement appears. The transfer function is characterised by a first peak located in the range of 0.9–2 Hz and a maximum amplification peak ranging from 3–8 Hz. The maximum amplification value ranges between 3 and 7.

The predominant frequency of Nakamura's technique exhibits values ranging between 0.8 and 2 Hz. We would like to point out the similarity between the predominant frequencies and the differences between the frequencies of maximum amplification in Zones I and II.

Zone III is characterised by superficial dynamic parameters similar to those in Zone II. Schematically, the subsoil column can be represented by a layer of Quaternary materials with thickness ranging from 10–15 metres on top of a Palaeozoic basement, more or less weathered. The transfer function is characterised by a first peak located in the range of 3–7 Hz and a maximum amplification peak located in the same values. The maximum amplification value ranges between 3 and 6. The predominant frequency of Nakamura's technique shows values ranging between 2.5 and 6.5 Hz, very similar to the maximum amplification peak of the transfer function.

It results that the predominant frequency of Nakamura's technique shows a good agreement with the first peak of amplification, or fundamental frequency, for the Post-Palaeozoic deposits, confirming the values estimated for the dynamic parameters used in the simulation.

Basically, we can distinguish two different frequencies in the transfer function computed for the 70 sites: the first peak of amplification, or fundamental frequency, and the frequency of the maximum amplification peak. For Zone III both frequencies are equal and for Zone I, both frequencies are similar. However, for Zone II the difference is very noticeable. The maximum amplification frequency is produced by the Quaternary sediments with a high impedance contrast. The fundamental frequency obtained in the numerical simulations and the predominant frequency obtained by Nakamura's technique seem to be greatly influenced by the thickness of the Tertiary materials, when these have a significant thickness as is the case of Zone II, according to detailed gravity data (SUSAGNA *et al.*, 1998).

Another consequence is that the predominant frequencies of Nakamura's technique provide information regarding the frequency in which maximum amplification of the soil response occurs in only certain situations. A warning should be given in the sense that although Nakamura's technique can give good approaches in some cases, in several other circumstances it will not estimate well the frequency for which the maximum amplification of the soil response occurs. Problems, possibilities and limitations of this method have been discussed by many authors (LERMO and CHÁVEZ-GARCIA, 1994; LACHET and BARD, 1994; MUCHARELLI, 1998, among others). But, in fact, the validity limits of applicability of this technique have not yet been well established. Therefore, Nakamura's technique cannot be the only basis for microzoning. This technique is very useful however it should always be applied together with numerical modelling using the most real geotechnical data possible and other experimental techniques such as SSR (Standard Spectral Ratio) when possible.

Conclusions

Information from geological maps, gravimetric surveys and standard geotechnical drillings for building and infrastructure constructions have been useful to determine dynamical parameters of soils in Barcelona.

A numerical 1-D equivalent linear method has been used to compute complete transfer functions and other spectral responses such as PSA and PSV in 70 sites, considering for each of them variations of the model through Monte-Carlo's simulation leading to significant dispersions. A grouping process has been applied in order to characterise the amplification of different zones of the city.

Given the observed uncertainties there has been a preference to present the results as mean transfer functions, and their corresponding standard deviation, defining the response for four large zones. This smoothing approach may lead to lower values of amplification than those obtained with individual samples which cannot be considered representative. For a detailed microzonation there is needed a better, detailed knowledge of the dynamic subsoil model not presently available.

The resulting four zones and their corresponding mean transfer functions with respect to outcropping Tertiary materials are presented in Figures 10 and 11. Table 2 shows, for each of these zones, the obtained values of PGA amplification, frequency of maximum amplification and maximum amplification factor. Zone I (Holocene deltaic materials) and Zone II (Pleistocene materials over a thick layer of Tertiary materials) show similar mean values of PGA amplification (near 1.7) and maximum amplification factor (2.5), however this maximum amplification occurs around 2.5 Hz in Zone I and around 5 Hz in Zone II. Zone III (Pleistocene over Palaeozoic basement) presents a mean value of PGA amplification of 1.43 and a maximum amplification factor of 2.25 at 5 Hz.

The obtained frequencies of maximum amplification are compared with those derived from microtremor measurements (Fig. 9). They differ little in Zones I and III although, in the case of Zone II, the Nakamura's frequencies seem to correspond to the fundamental frequency which in this case is not the frequency of interest, i.e., the frequency for which the maximum amplification occurs. It is then recommended not to base microzoning only on experimental Nakamura's technique without comparison with other methods.

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References

ALFARO, A. (1997), *Estimación de períodos predominantes de los suelos de Barcelona a partir de microsismos*, Thesis of Master. Universitat Politècnica de Catalunya; 69 pp.

ALFARO, A., GUTIÉRREZ, F., SUSAGNA, T., FIGUERAS, S., GOULA, X., and PUJADES, L. (1997), *Measurements of microtremors in Barcelona: A tool for seismic microzonation*. In *Proc. Third Annual Conf of the Internat. Assoc. for Math. Geology (IAMG'97)*. International Center for Numerical Methods in Engineering (CIMNE), vol. 2, (Barcelona 1997), pp. 917–921.

ALFARO, A., PUJADES, L. G., GOULA, X., SUSAGNA, T., NAVARRO, M., SANCHEZ, J., and CANAS, J.A. (2001), *Preliminary Map of Soil's Predominant Period in Barcelona Using Microtremors*, Pure appl. geophys. (this issue).

AMIEIRO, C. and CID, J. (1999), *Análisis de riesgo sísmico del plan específico de emergencia municipal de Barcelona*. In *Proc. 1er Congreso Nacional de Ingeniería Sísmica. Asociación Española de Ingeniería Sísmica*. vol. Ia, 321–330.

AUTH, SF (1997), Annual Report. *Euro-Seismod. Project: ENV4-CT96-0255, CEC, DGXII*, Development and experimental validation of advanced modelling techniques in engineering seismology and earthquake engineering.

BARCHIESI, A. M., CID, J., FIGUERAS, S., SUSAGNA, T., FLETA J., and GOULA, X. (1997), *Influence of the geotechnical parameters on seismic local effects in Barcelona*. In *Proc. Third Annual Conf of the Internat. Assoc. for Math. Geology (IAMG'97)*. International Center for Numerical Methods in Engineering (CIMNE), vol. 2, (Barcelona 1997), pp. 922–927.

Bard, P. Y. and Bouchon, M. (1980a), *The Seismic Response of Sediment-filled Valleys. The Case of Incident SH Waves*, Bull. Seismol. Soc. Am., *70*, 1263–1286.

Bard, P. Y. and Bouchon, M. (1980b), *The Seismic Response of Sediment-filled Valleys. The Case of Incident P and SV Waves*, Bull. Seismol. Soc. Am., *70*, 1921–1941.

Borcherdt, R. D. (1994), *Estimates of Site-dependent Response Spectra for Design (Methodology and Justification)*, Earthquake Spectra. *10*, 4, 617–653.

Chávez-García, F. J. and Bard, P. Y. (1994), *Site Effects in Mexico City Eight Years after the September 1985 Michoacan Earthquakes*, Soil Dyn. Earthq. Eng. *13*, 229–247.

Cid, J. (1996), *Estimació dels paràmetres dinàmics dels sòls, procediment i aplicació a Barcelona.* Thesis of Master. Universitat Politècnica de Catalunya, 227 pp.

Cid, J. (1998), *Zonación sísmica de la ciudad de Barcelona basada en métodos de simulación numérica de efectos locales*, Ph.D.Thesis. Universitat Politècnica de Catalunya, 215 pp.

Dickenson, S. E. and Seed, R. B. (1996), *Nonlinear dynamic response of soft and deep cohesive soil deposits*, In *Proc. Internat. Workshop on Site Response Subject to Strong Earthquake Motions*, Yokosuka, Japan, vol. 2, pp. 67–81.

Figueras, S., Schmidt, V., Susagna, T., Fleta, J., Goula, X., and Roca, A. (1995), *Preliminary study of microzonation of Barcelona.* In *Proc. Fifth Internat. Conf. on Seismic Zonation*, vol. 1, pp. 731–738.

Goula, X., Susagna, T., Fleta, J., and Secanell, R. (1998a), *Informació territorial i anàlisi del risc pel pla SISMICAT. Part I: Perillositat Sísmica*, Report Institut Cartogràfic de Catalunya. No. GSI65/98.

Goula, X., Susagna, T., Figueras, S., Cid, J., Alfaro, A., and Barchiesi, A., (1998b) *Comparison of numerical simulation and microtremor measurement for the analysis of site effects in the city of Barcelona (Spain)*, In *Eleventh European Conf. on Earthquake Engineering* (Balkema. CD-ROM 1998b).

Iai, S., Morita, T., Kaameoka, T., Matsunaga, Y., and Abiko, K. (1995), R*esponse of a Dense Sand Deposit During 1993 Kushiro-Oki Earthquake*, Soils and Foundations *35*(1), 115–131.

Icc (2000), *Mapa Geotècnic de Barcelona E 1:25000*. CD-ROM, Institut Cartogràfic de Catalunya, Barcelona.

Idriss, I. M. and Sun, J. I. (1992), *User's Manual for Shake'91: A Computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits*, Department of civil and Environmental Engineering, Davis, CA, 13 pp.

Jiménez, M. J., García-Fernández, M., Zonno, G., and Cella, F. (2000), *Mapping soil effects in Barcelona, Spain, through an integrated GIS environment*. In *Soil Dynamics and Earthquake Engineering* (Elsevier 2000) vol. 19, no. 4, pp. 289–301.

Jongmans, D. and Campillo, M. (1993), *The Response of the Ubaye Valley (France) for Incident SH and SV Waves: Comparison Between Measurements and Modeling*, Bull. Seismol. Soc. Am. *83* (3), 907–924.

Lachet, C. and Bard, P. Y. (1994), *Numerical and Theoretical Investigations on the Possibilities and Limitations of the Nakamura's Technique*, J. Phys.Earth *42*, 377–397.

Lermo, J. and Chávez-Garcia, F. J. (1994), *Are Microtremors Useful in Site Response Evaluation?* Bull. Seismol. Soc. Am. *84*(5), 1350–1364.

Lázaro, R., Vilas, M., Rivero, L., Pinto., V., Bagán, L., and Casas, A. (1998), *Determinación de las isobatas del zócalo de la ciudad de Barcelona a partir de la interpretación de las anomalías gravimétricas*, *I* Asamblea Hispano-Portuguesa de Geodesia y Geofísica. CD-ROM. Instituto Geográfico Nacional, Madrid.

Lo Presti, D. C. F. and Lai, C. (1989), *Shear-wave velocity from penetration tests*, Politecnico di Torino. Dipartimento di Ingegneria Strutturale. Atti del Dipartimento, vol. 21, 32 pp.

Losan (1978), *Mapa geotécnico de Barcelona, Badalona, Esplugues, L'Hospitalet, Sant Adrià y Sta.* Coloma. Barcelona, 32 pp., 1 map.

Mucciarelli, M. (1998), *Reliability and Applicability of Nakamura's Technique Using Microtremors: An Experimental Approach*, J. Earthq. Eng. *2*(4), 625–638.

Nakamura, Y. (1989), *A Method for Dynamic Characteristics Estimation of Subsurface Using Microtremors on the Ground Surface*, Quarterly Report of Railway Technical Research Institute *30-1*, 25–33.

NCSE-94 (1995), *Normativa de Construcción Sismorresistente Española NCSE-94*, Real Decreto 2543/94. Boletín Oficial del Estado (B. O. E.) *33* (8th of February 1995).

PECKER, A. (1995), *Validation of Small Strain Properties from Recorded Weak Seismic Motions*, Soil Dyn. Earthq. Eng. *14*, 399–408.

RIEPL, J. (1997), *Effects de site: évaluation expérimentale et modélisations multidimensionnelles. Application au site-test EUROSEISTEST (Gréce)*, Ph.D. Thesis. Université Joseph Fourier de Grenoble, 227 pp.

SECANELL, R. (1999), *Avaluació de la perillositat sísmica a Catalunya: Análisi de sensibilitat a diferents models d'ocuurència i paràmetres sísmics*, Ph.D. Thesis. Universitat de Barcelona, 335 pp.

SUSAGNA, T., CID, J., LÀZARO, R., GOULA, X., CASAS, A., FIGUERAS, S., and ROCA, A. (1998), *Applying microtremor, gravity anomalies and numerical modelling methods for the evaluation of soil earthquake response in Barcelona, Spain.* In *Proc. IV Meeting of the Environmental and Engineering Geophysical Society* (Barcelona 1998) pp. 651–654.

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161