Comparison of numerical simulation and microtremor measurement for the analysis of site effects in the city of Barcelona (Spain)

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ABSTRACT: Barcelona is spread over several geological units: Paleozoic and Tertiary materials outcrops with Pleistocene and Holocene deposits placed over them. Each one of these units is characterised by significantly different geotechnical parameters. An accurate geotechnical study has been carried out with the estimation of the dynamic properties of the subsoil in the zone. Two different techniques have been applied to evaluate the potential seismic site effects. The results of a simulated transfer functions using a unidimensional linear-equivalent method have been compared with the predominant frequency of the Nakamura's technique carried out in about 70 points. Through different analysis we can explain that the predominant Nakamura's frequency is related to the thickness of Post-Paleozoic materials. Sometimes, the maximum amplification is found at the higher frequencies produced by the impedance contrast of Quaternary and Pre-Quaternary materials.

1 INTRODUCTION

Although the city of Barcelona is considered as a zone of moderate seismic activity, and rated with an MSK VI intensity for a return period of 500 years by the Spanish Seismic Code (NCSE-94 1995), other factors can aggravate the seismic hazard and, therefore, make its assessment necessary. These factors are: the high population density, the *artistic patrimony* with constructions of high vulnerability, and the presence of deltaic materials of low geotechnical quality which come from the Besòs and Llobregat rivers.

Some studies have been carried out, in the past, related to risk assessment of the city: a preliminary study of microzonation with the evaluation of five transfer functions based on unidimensional methods (Figueras et al. 1995); a methodological study allowing an empirical estimation of the dynamic parameters of soils (Cid 1996); creation and exploitation of a geotechnical database (Cid 1997a, b, c, d, e); a study on the sensitivity of geotechnical parameters on local seismic effects (Barchiesi 1997, Barchiesi et al. 1997); application of the Nakamura (1989) method to the measurement of environmental noise (microtremors) (Alfaro 1997, Alfaro et al. 1997, Alfaro et al., in press.).

With the aim of defining a preliminary microzonation of Barcelona, 45 transfer functions have been evaluated using a unidimensional linear-equivalent method. Their results allow the characterisation of three different zones. We show the comparison of the results obtained applying the Nakamura's technique with those obtained by the computed transfer functions. The differences and similarities found between them are discussed in this paper.

2 LOCAL GEOLOGICAL SETTING

The city of Barcelona is located on the Mediterranean coast, occupying the pediment of the Catalan Coastal Range, which runs parallel to the coastline. Its boundaries are the Besòs Delta on the NE and the Llobregat Delta on the SW. Two geomorphologic units can be recognised. First, the mountainous profiles which consist of Paleozoic and Tertiary materials. Second, the plain of Barcelona, which is itself divided into another two geomorphologic units, separated by a steep talus that presents an unevenness of approximately 20-30 m: the pediment plain, made of Pleistocene materials, and Holocene materials from the mouths of the Besòs and Llobregat rivers (Figs 1-3).

The Paleozoic materials (Ordovician-Carboniferous) are basically composed of sedimentary materials, which have been affected by different degrees of metamorphism, and of plutonic materials: granites. The latter are, quite frequently, found superficially altered, being called *Sauló* by the local people. The Tertiary materials (Miocene-Pliocene) lay discordantly on top of the older ones. The Miocene is composed of a marine sequence of blue marls levels, fossiliferous, red-grey sandstones and metric conglomerate levels. The Pliocene, of smaller extension, is represented by a marine sequence of marls and sands (Figueras et al. 1995).

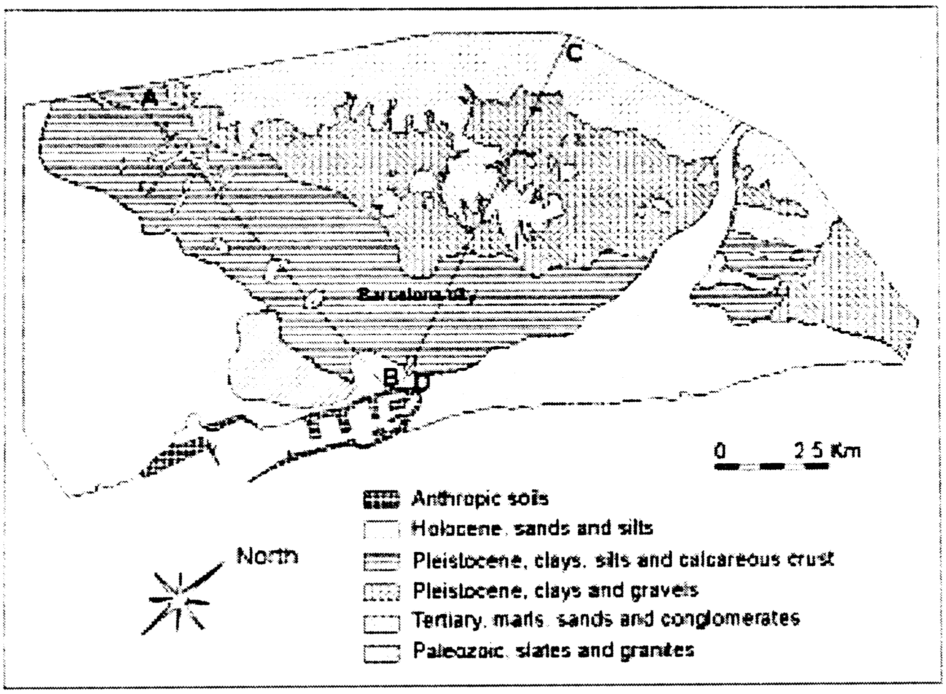

Figure 1. Geological map of the zone under study. The straight lines A-B, C-D represent the geographical location of the geological cross sections of Figures 2-3 (modified from Losan 1978).

The Pleistocene terrains, locally known as *Triciclo*, are discordant in relation to the Paleozoic or Tertiary materials, depending on the zone. Their thickness normally ranges between 10-25 m and they are composed of a cyclic series of red clays, eolian silts, calcareous crusts and gravels. Being predominantly detrital, they have plenty of gravels near the mountainous profiles. The Holocene terrains are discordant in relation to the Paleozoic or Tertiary materials -depending on the zone of the Besòs delta- and are discordant in relation to the Tertiary materials only in the zone of the Llobregat delta. They are composed of sands, muds and rounded gravels. The deltaic terrains of the Besòs river are different from those coming from the Llobregat river, mainly due to their thickness, which is 50 m for the first and 100 m for the second (Losan 1978).

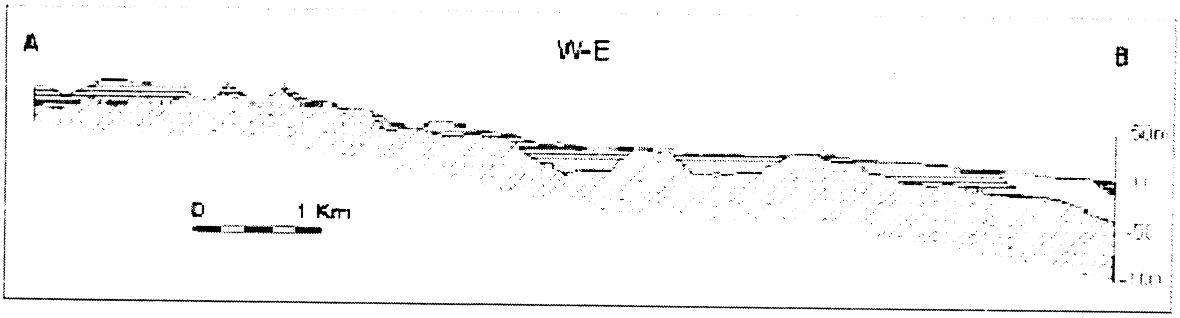

Figure 2. Geological cross-section *Riera de la Fontsanta-Drassanes*. Symbology and location in Figure 1. (Modified from Losan 1978).

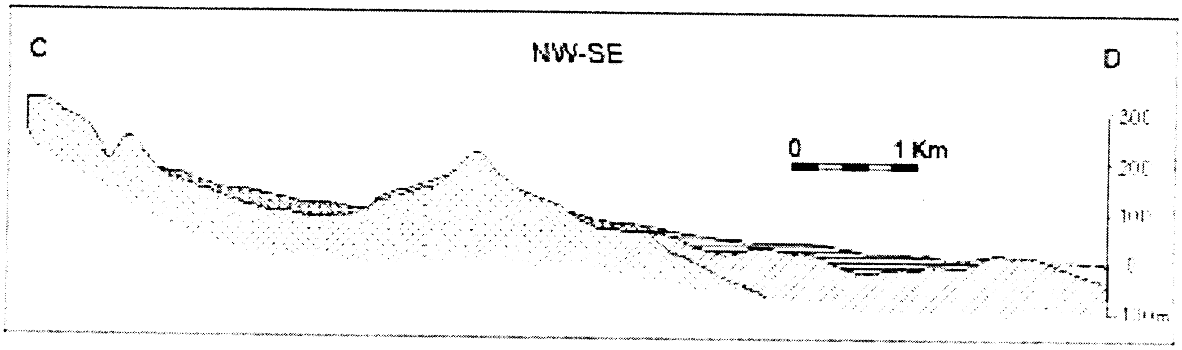

Figure 3. Geological cross-section *Turò d'en Fotjà-Passeig de Colom*. Symbology and location in Figure 1. (Modified from Losan 1978).

3 DYNAMIC CHARACTERISATION OF THE SUBSOIL

In order to model the local amplification effects, it is necessary to estimate the dynamic parameters of the materials existing between the basement and the surface of the terrain. This model requires the estimation of parameters such as the shear wave velocity (V_s), the maximum dynamic shear module (G_{max}), the density (ρ) and the thickness of the layers.

These dynamic parameters are evaluated in different ways, based on their depth and depending upon the presence of geotechnical data. So, a methodology that allows the evaluation of dynamic parameters of the soil starting from geotechnical parameters used in civil works (Cid 1996) is used for the first metres of the analysed subsoil. This solves the problem of the absence of experimental values of dynamic soil properties for Barcelona. We estimate from standard penetration tests (SPT) or other penetration tests, a soil column with an homogeneous N-value for each layer, in a representative sense, of the zone under study. This N-value is empirically correlated to the shear wave velocity of the layer through the equation 1 (Lo Presti & Lai 1989).

$$V_s = 68.79 \cdot N^{0.171} \cdot Z^{0.199} \cdot F_A \cdot F_G \qquad (1)$$

where V_s=Shear wave velocity in m/s; N=Value from the standard penetration test; Z=Depth in m; F_A=Age factor (see Table 1); F_G=Granulometry factor (see Table 2).

Table 1. Age factor for equation 1.

	Holocene	Pleistocene
F_A	1	1.303

Table 2. Granulometry factor for equation 1.

	Clay	Fine sand	Medium sand	Coarse sand	Sand & gravel	Gravel
F_G	1	1.086	1.066	1.135	1.153	1.448

For values of N≤50, this methodology allows us to obtain the shear wave velocity. For N>50, V_s has been estimated on the basis of factors such as age, compaction, depth, lithology, a geologic sense, etc. The density values are obtained from specific or general measurements in the geotechnical reports of the studied zones. These values have been previously introduced in the geotechnical database of Barcelona (Cid 1997a). The maximum dynamic shear modulus is obtained from the equation 2.

$$G_{max} = V_s^2 \cdot \rho \tag{2}$$

The remaining dynamic parameters, down to the Paleozoic basement, have been estimated considering such factors as depth, lithology, alteration degree and previous studies, i.e. studies of inversion of detailed gravity surveys (Casas, pers. comm., Barchiesi et al. 1997, Figueras et al. 1995, Losan 1978).

These procedures have been applied to 45 points in the city of Barcelona. The results can be observed in Figures 4-5. For the first metres, these are only based on geotechnical considerations. For the remaining of the column, down to the Paleozoic basement, the results are mainly based on studies of detailed gravity surveys and the kinds of lithology.

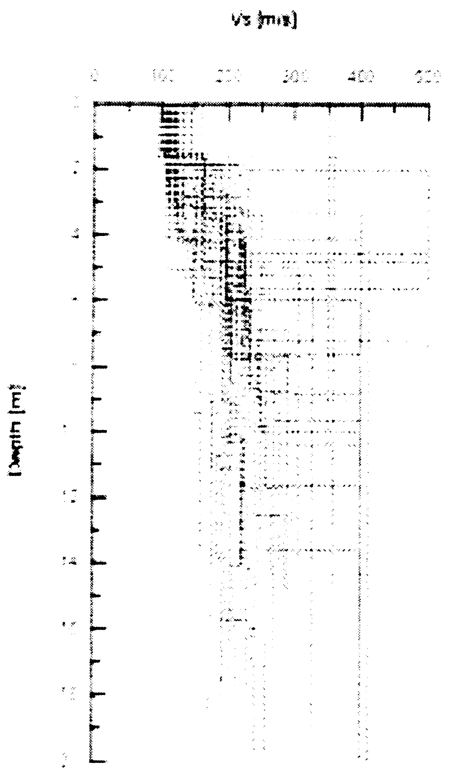

Figure 4. Variation of the shear wave velocity-depth for the first 20 metres.

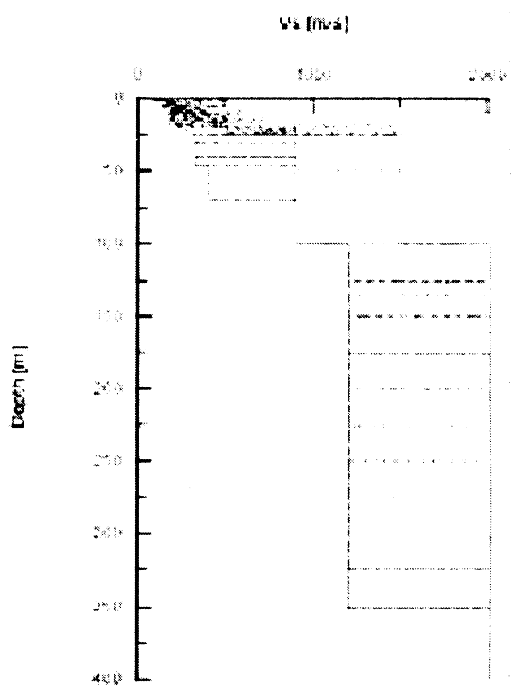

Figure 5. Variation of the shear wave velocity- depth.

4 PREDOMINANT FREQUENCY (NAKAMURA'S TECHNIQUE)

The Nakamura's technique has been applied to environmental noise (microtremors) measurements. These have been carried out at about 70 points, giving a good coverage of the various districts of the city and being significant of the different soil structures according to the known geological and geotechnical data (Losan 1978). A 19 bit resolution, tri-axial Strong Motion Accelerograph (Kinemetrics-K2) has been used. Several records of three minutes duration were obtained for every site. The sampling rate used was 100 samples per second. The spectral ratios H/V were computed from the smoothed average spectra (Alfaro 1997, Alfaro et al. 1997).

The predominant frequency (or frequency for the maximum amplification of the H/V spectral ratio) is obtained in some of the studied points. These predominant frequencies are shown in Figure 6. Three different zones can be distinguished: 1) Paleozoic and Tertiary materials without a significant predominant frequency; 2) Upper part of the town, with a predominant frequency above 2.5 Hz; and 3) Lower part of the town with a predominant frequency in the range of 0.6-2.5 Hz. The third zone, characterised by low frequencies, shows an extension which is in agreement with the deepest Paleozoic basement, determined by detailed gravity studies (Lázaro, in press.).

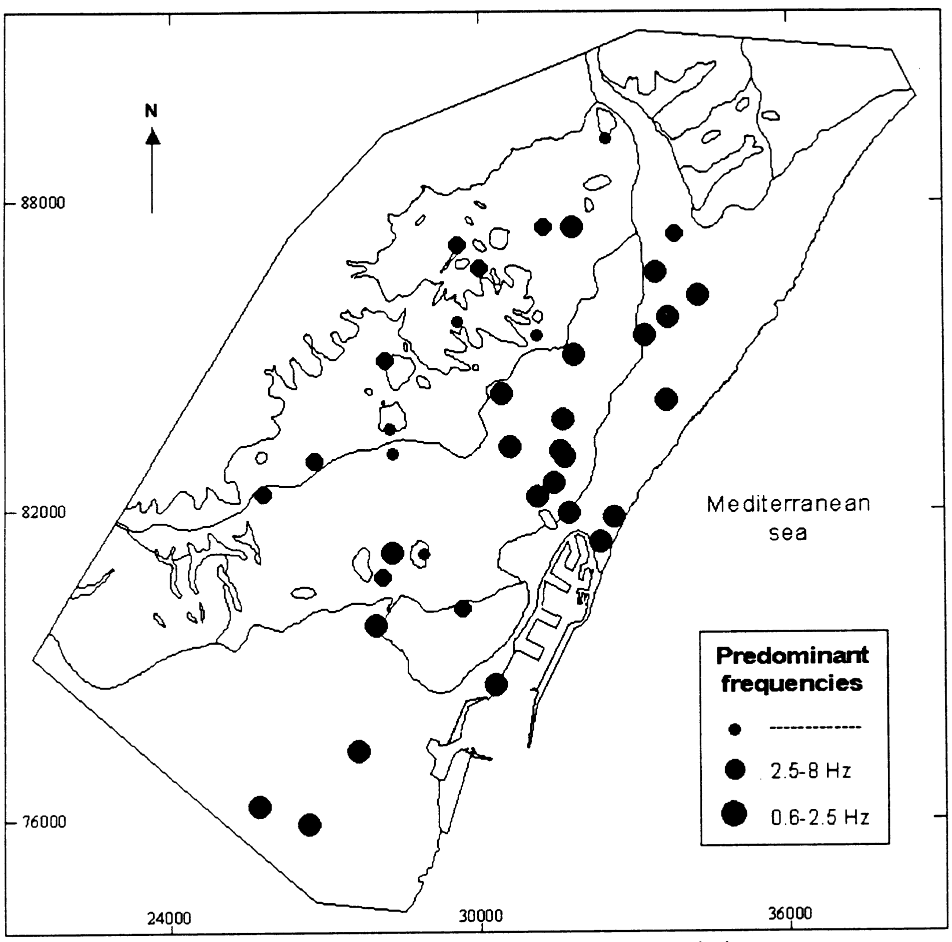

Figure 6. Predominant frequencies obtained by Nakamura's technique.

5 TRANSFER FUNCTIONS

The dynamic characterisation of 45 points of the subsoil, described in section 3, has been used to compute the transfer functions. Two unidimensional methods were tested: the reflectivity method (Kennett & Kerry 1979) and the linear-equivalent, Shake'91 (Idriss & Sun 1991). The results obtained by both methods show a great agreement. We show the results obtained by the unidimensional, linear-equivalent method, Shake'91. All the computed transfer functions have been normalised with respect to a reference point (on the basis of the relative spectral ratio). We define, as the reference point of the Barcelona city, the non-weathered Paleozoic basement.

An input motion of 0.04 g was used, according to the PGA value stated in the Spanish Seismic Code (NCSE-94 1995). The variation curves for the dynamic shear modulus and the damping ratio with shear strain are deduced from recent data obtained in the Volvi Valley, Greece (Pitilakis, pers. comm.).

A preliminary seismic zonation (Fig. 7) is proposed, based on the transfer function and the Pseudo-Acceleration Spectra (PSA), with 5% damping, obtained for each one of the 45 sites. The six parameters below have been used:

1. First peak of the transfer function
2. Shape of the transfer function
3. PSA_{soil}
4. PSA_{soil} normalised to the PGA_{soil}
5. $(PSA_{soil}/PGA_{soil}) / (PSA_{rock}/PGA_{rock})$
6. Accumulated area of the relationship 5

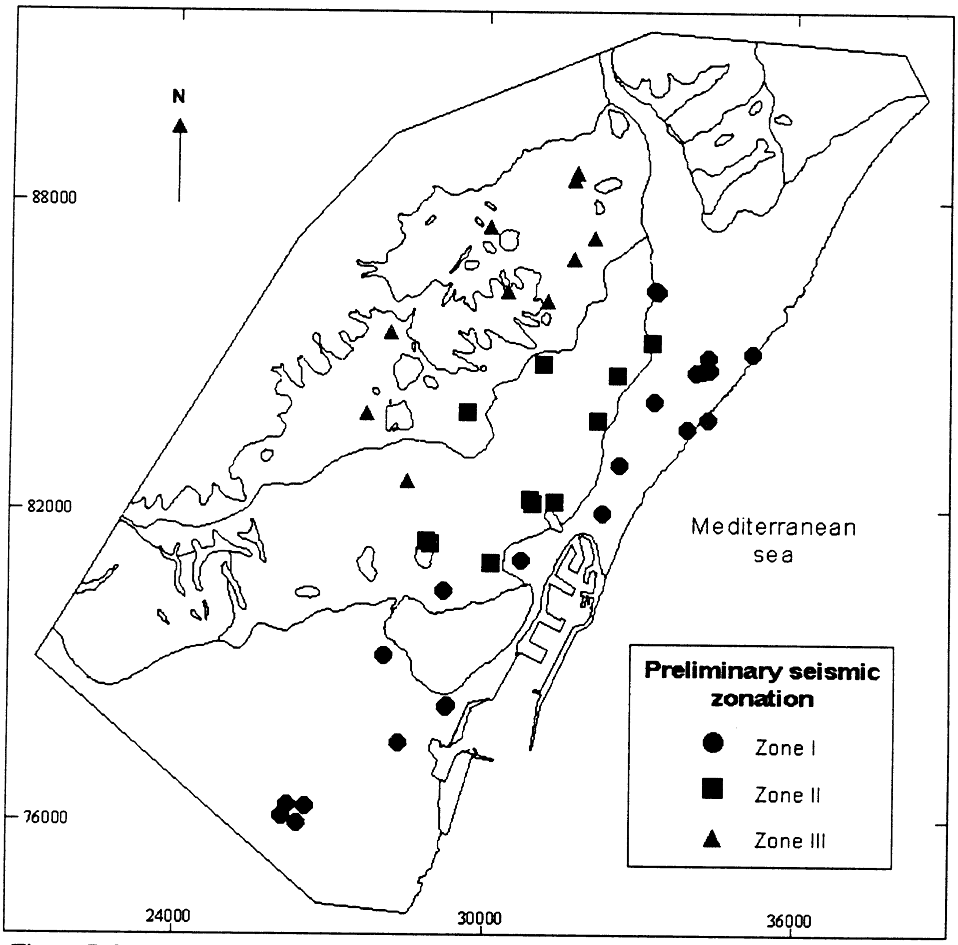

Figure 7. Preliminary seismic zonation of the city of Barcelona. Based on 45 study points.

Figures 8-10 show, for each zone: 1) the transfer functions corresponding to the different sites, grouped following the criteria mentioned above; 2) the average transfer function; and 3) the average plus and minus one standard deviation. In order to compare the transfer functions obtained to the predominant frequencies obtained by Nakamura's technique (Fig. 6), the average of the predominant frequency of Nakamura's technique is also shown.

Zone I (Fig. 8) is characterised by outcrops of Holocene deltaic materials with an average shear wave velocity of around 200 m/s for the first metres (around 20 metres). Schematically, the subsoil column can be represented by a layer of Quaternary materials with thicknesses in the range of 25-70 metres on top of another very thick layer of Tertiary materials. Under these layers we find the Paleozoic basement, at depths of less than 350 m (Casas, pers. comm.). The transfer function is characterised by a first peak 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, showing a high attenuation for higher frequencies. The predominant frequency of the Nakamura's technique shows values ranging between 0.8 and 2 Hz.

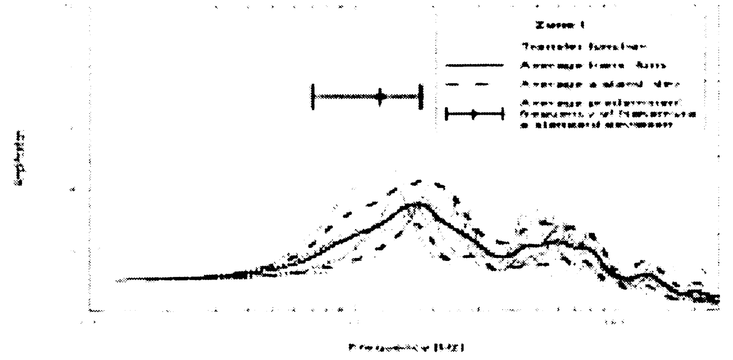

Figure 8. Computed transfer functions for Zone I sites (Fig. 7) and average predominant frequency of the Nakamura's technique.

Zone II (Fig. 9) 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 thicknesses in the range of 10-25 metres on top of another layer of Tertiary materials reaching a depth of 100-350 metres, where the Paleozoic basement appears (Casas, pers. comm.). The transfer function is characterised by a first peak located in the range of 0.9-2 Hz and a maximum amplification peak in the range of 3-8 Hz. The maximum amplification value ranges between 3 and 7. The predominant frequency of the Nakamura's technique shows values ranging between 0.8 and 2 Hz. We would like to point out the similarity between the predominant frequencies in zone I and zone II.

Zone III (Fig. 10) 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 thicknesses in the range of 10-15 metres on top of a Paleozoic 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 the Nakamura's technique shows values ranging between 2.5 and 6.5 Hz, very similar to the maximum amplification peak of the transfer function.

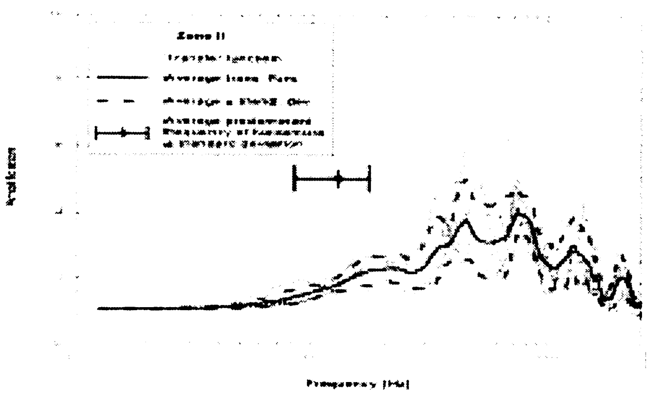

Figure 9. Computed transfer functions for Zone II sites (Fig. 7) and average predominant frequency of the Nakamura's technique.

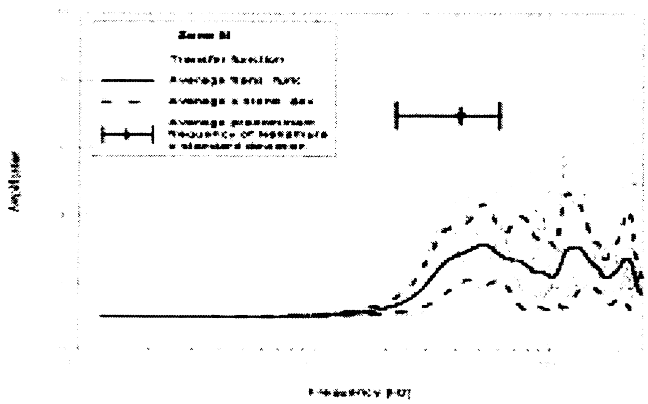

Figure 10. Computed transfer functions for Zone III sites (Fig. 7) and average predominant frequency of the Nakamura's technique.

6 DISCUSSION

It is known that the Nakamura's technique does not inform about the amplification factor of the subsoil. It is also known that this technique only gives information about the fundamental mode, or first peak, of the transfer function but does not give any indication about the amplification at higher frequencies (Lachet & Bard 1994). The Nakamura's technique presents three main problems: 1) Only informs about one frequency of amplification; 2) Does not give any information about the amplification factor; and 3) In the case that the maximum amplification and the fundamental frequency are not the same, some misinterpretations may arise.

Figure 11 shows graphically the relationship between the predominant frequency of the Nakamura's technique and the first peak of amplification, <20Hz, found in the simulation, indicating a good correlation. Conversely, the frequency <20Hz for the maximum amplification, found in the simulation, does not correlate with the predominant frequency of the Nakamura's technique (Fig. 12).

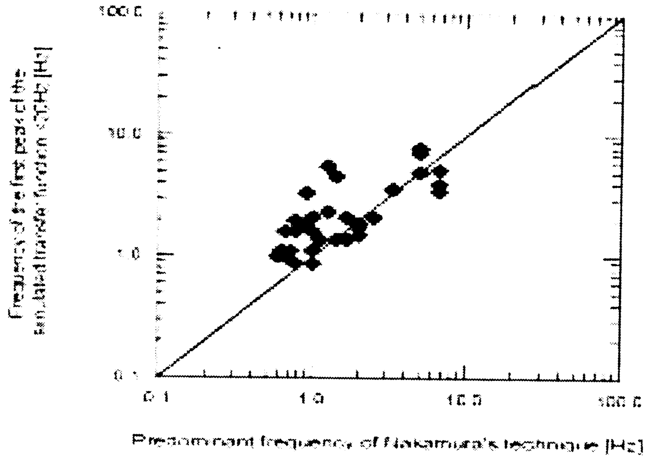

Figure 11. Relationship between the predominant frequency of the Nakamura's technique and the frequency of the first peak of the simulated transfer function <20Hz.

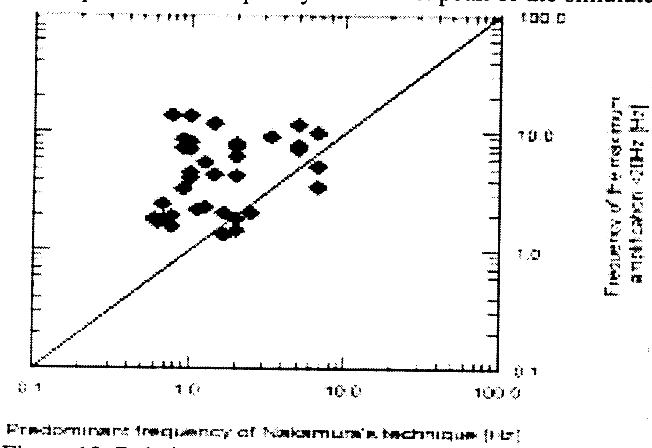

Figure 12. Relationship between the predominant frequency of the Nakamura's technique and the frequency of the maximum amplification <20Hz

The fundamental frequency obtained according to equation 3, for the average shear wave velocity in Post-Paleozoic deposits, used in the computation of transfer functions, shows a good agreement with the predominant frequency obtained by the Nakamura's technique (Fig. 13). On the other hand, the average shear wave velocity in Quaternary deposits gives a fundamental frequency which is in disagreement with the predominant frequency obtained by the Nakamura's technique (Fig. 14).

$$f_0 = \frac{V_s}{4 \cdot H} \qquad (3)$$

where f_0=Fundamental frequency; V_s=Shear wave velocity in the layer; H=Thickness of the layer.

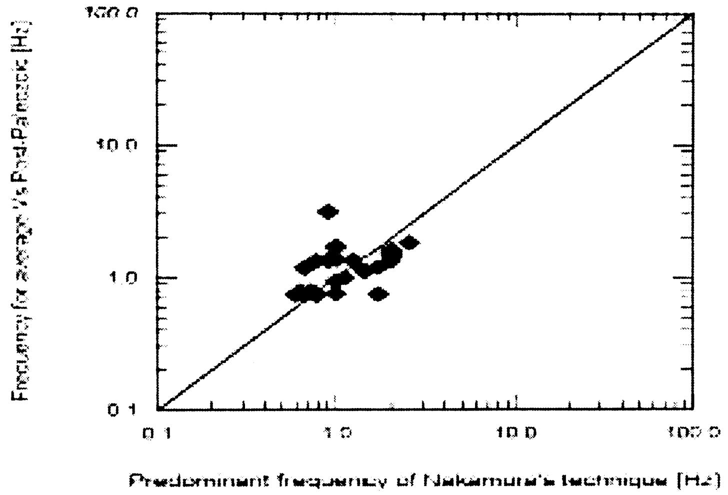

Figure 13. Relationship between the predominant frequency of Nakamura's technique and the frequency of the simulated first peak of amplification for the average shear wave velocity in Post-Paleozoic deposits.

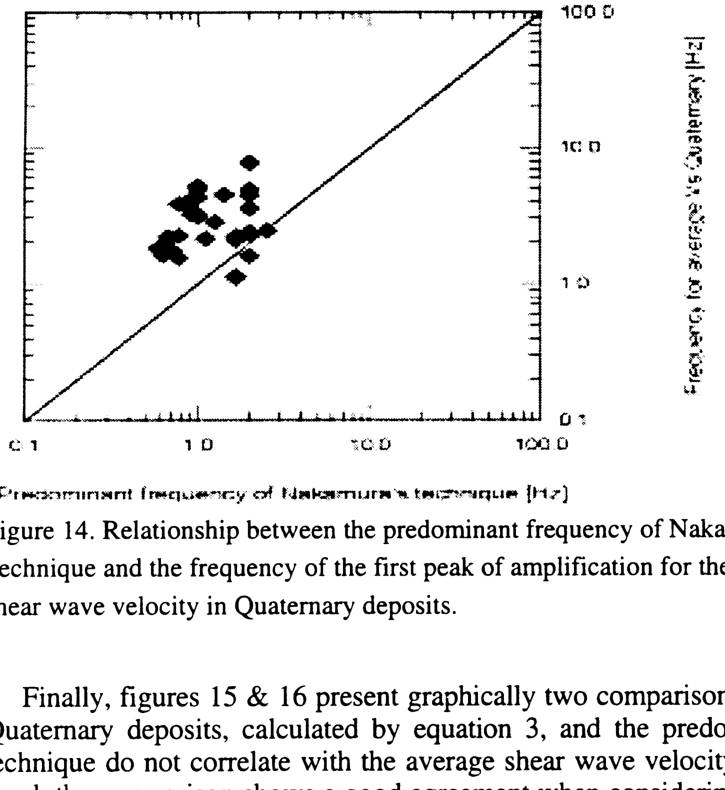

Figure 14. Relationship between the predominant frequency of Nakamura's technique and the frequency of the first peak of amplification for the average shear wave velocity in Quaternary deposits.

Finally, figures 15 & 16 present graphically two comparisons. The average shear wave velocity in Quaternary deposits, calculated by equation 3, and the predominant frequency of the Nakamura's technique do not correlate with the average shear wave velocity used in the simulation. On the other hand, the comparison shows a good agreement when considering the Post-Paleozoic deposits. We can observe, in Figure 15, the small value of the average shear wave velocity in Quaternary deposits, less than 50 m/s, necessary to explain the values found in the Nakamura's technique for the city of Barcelona.

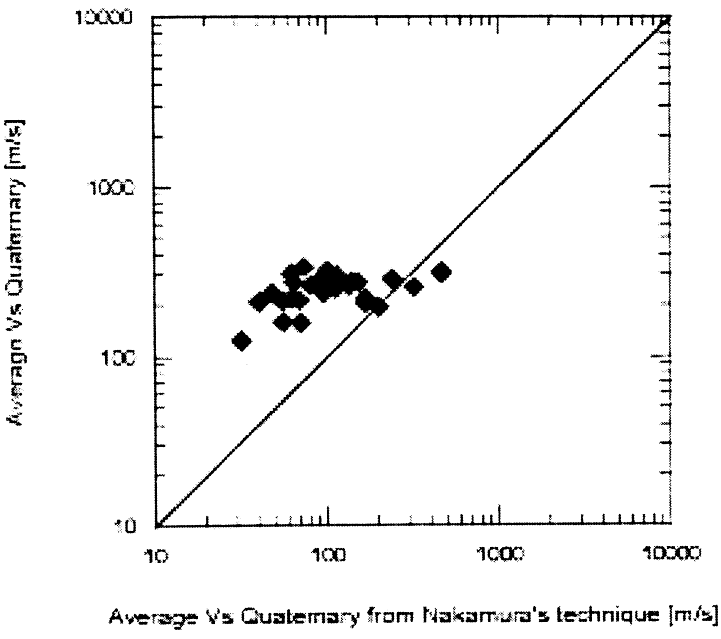

Figure 15. Relationship between the average shear wave velocity in Quaternary deposits and the average wave velocity used in the simulation.

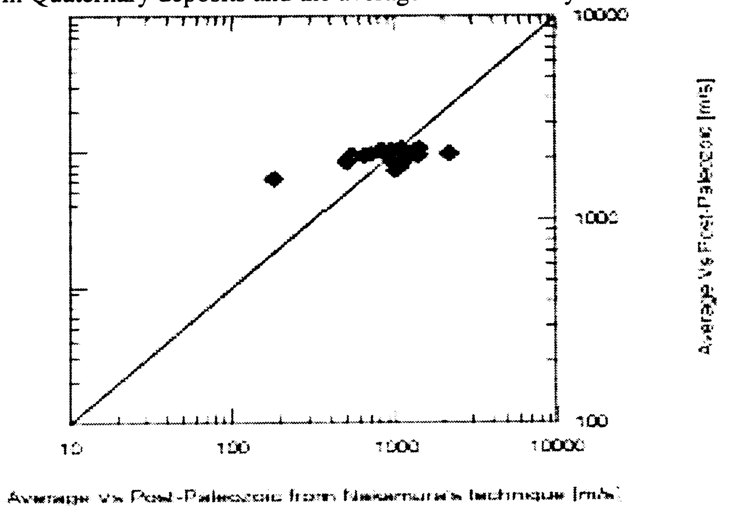

Figure 16. Relationship between the average shear wave velocity in Post-Paleozoic deposits and the average wave velocity used in the simulation.

In our case, and generally speaking, the predominant frequency of the Nakamura's technique shows a good agreement with the first peak of amplification, or fundamental frequency, for the Post-Paleozoic deposits. This verification confirms 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 45 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 fundamental frequency seems to be greatly influenced by the thickness of the Tertiary materials, when these have a significant thickness. The maximum amplification frequency is produced by the Quaternary sediments with a high impedance contrast.

In consequence, the predominant frequency obtained, in Barcelona, by the Nakamura's technique seems to be in agreement with the depth of the Paleozoic basement deduced from the studies of a detailed gravity survey (Lázaro, in press.). Conversely, it does not seem to correlate with the depth of superficial Quaternary deposits. Another consequence, for Barcelona, is that the predominant frequency obtained by the Nakamura's technique is related to the small impedance contrast existing between Tertiary and Paleozoic materials, and not to the high impedance contrast existing between Quaternary and Tertiary or Paleozoic materials

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REFERENCES

Alfaro, A. 1997. Estimación de períodos predominantes de los suelos de Barcelona a partir de microterremotos. *Thesis of Master. Universitat Politècnica de Catalunya:* 69.

Alfaro, A., Gutiérrez, F., Susagna, T., Figueras, S. Goula, X. & Pujades, L. 1997. Measurements of microtremors in Barcelona: a tool for seismic microzonation. *Proceedings of IAMG'97.* Vol 2: 917-921. Barcelona:CIMNE.

Alfaro, A., Goula, X., Susagna, T., Pujades, L.G., Canas, J.A., Navarro, M. & Sánchez, J. 1998. (In press.). Estimación del período predominante del suelo a partir de microtemblores. Aplicación a Barcelona. *I Asamblea Hispano-Portuguesa de Geodesia y Geofísica. IX Asamblea Nacional de Geodesia y Geofísica.*

Barchiesi, A.M. 1997. Influencia de los parámetros geotécnicos sobre los efectos dinámicos locales en Barcelona. *Thesis of Master. Universitat Politècnica de Catalunya:* 127.

Barchiesi, A.M., Cid, J., Figueras, S., Susagna, T., Fleta, J. & Goula, X. 1997. Influence of the geotechnica parameters on seismic local effects in Barcelona. *Proceedings of IAMG'97.* Vol 2: 922-927. Barcelona:CIMNE.

Casas, A. 1997. Personal communication.

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

Cid, J. 1997a. Aplicación GeotHDS [2.00] de explotación de la base de datos geotécnicos de la ciudad de Barcelona. *A.B. Report 7104097:* 92.

Cid, J. 1997b. Estimación de los parámetros dinámicos de los suelos en tres puntos de la ciudad de Barcelona. *A.B. Report 284097:* 44.

Cid, J. 1997c. Estimación de los parámetros dinámicos de los suelos en diez puntos de la ciudad de Barcelona. *A.B. Report 394097:* 73.

Cid, J. 1997d. Estimación de los parámetros dinámicos de los suelos en once puntos de la ciudad de Barcelona. *A.B. Report 494097:* 66.

Cid, J. 1997e. Estimación de los parámetros dinámicos de los suelos en nueve puntos de la ciudad de Barcelona. *A.B. Report 5104097:* 74.

Figueras, S., Schmidt, V., Susagna, T., Fleta, J., Goula, X. & Roca, A. 1995. Preliminary Study of Microzonation of Barcelona. *Proceedings of the fifth International Conference on Seismic Zonation.* Vol. 1: 731-738.

Kennett, B.L.N. & Kerry, N.S. 1979. Seismic waves in a stratified half space. *Geophys. Journal Royal Astron. Soc.* Vol. 57: 557-583.

Idriss, I. M. & Sun J. I. 1992. Shake'91: a computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits. *User's Guide. University of California:* 13.

Lachet, C. & Bard, P.Y. 1994. Numerical and theoretical investigations on the possibilities and limitations o the Nakamura's technique. *Jour. Phys. Earth.* 42: 377-397.

Lázaro, R. Rivero, L. Pinto. V. & Casas, A. 1997. (In press.). 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. IX Asamblea Nacional de Geodesia y Geofísica.*

Lo Presti, D.C.F. & Lai, C. 1989. Shear wave velocity from penetration tests. *Politecnico di Torino. Dipartimento di Ingegneria Strutturale. Atti del dipartimento.* Vol. 21: 32.

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

Nakamura, Y, 1989. A method for dynamic characteristics estimation of subsurface using microtremors on the ground surface. *Quarterly Report of Railway Technical Research Institute*. Vol. 30-1: 25-33.

NCSE-94, 1995. Normativa de Construcción Sismorresistente Española NCSE-94. *Real Decreto 2543/94. B.O.E. 33.* The 8th of February 1995.

Pitilakis, K. 1997. Personal communication.