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Preliminary Map of Soil's Predominant Periods in Barcelona Using Microtremors

A. Alfaro,[1] L. G. Pujades,[1] X. Goula,[2] T. Susagna,[2] M. Navarro,[3] J. Sánchez,[3] and J. A. Canas[4]

Abstract— In order to evaluate soil effects in the urban area of Barcelona, the Nakamura's technique has been used to estimate the predominant periods of soils. Noise measurements for 195 sites were performed using a strong motion accelerograph and a velocimeter. In this work, the resulting preliminary map of predominant periods is presented. The obtained predominant periods are coherent with the geological and geotechnical features of the area. The analysis of the information has allowed the distinctions among several types of soil and underlying materials. A predominant period of about 0.06 s is evaluated for sites located over outcrop Paleozoic rock in the Tibidabo-Collserola Mountains. For sites consisting of material named tricycle, that is the most extensive and also the most heterogeneous zone, predominant period range from 0.10 s up to 2.0 s depending on the thickness of the surface materials and the kind and thickness of the underlying materials. In the Besòs river two zones are observed: the riverside with periods between 0.50 s and 0.83 s and a second area with periods between 1.0 and 2.1 s. In the Llobregat river delta the obtained periods are quite homogeneous with values around 0.72 s. Other predominant periods are found in some tertiary rock outcrop.

Key words: Microtremor, Nakamura's technique, subsurface geology, Barcelona.

Introduction

Seismic microzonation studies imply the analysis of (1) the regional seismic hazard, starting from the active tectonics structures also called seismogenic areas; (2) the local hazard, starting from the modification of the seismic signal due to the geological and geotechnical local conditions; and finally, (3) induced phenomena such as liquefaction, settlements, landslides and others (AFPS, 1995).

[1] Technical University of Catalonia, Geotechnical Engineering and Geosciences, Spain.
E-mail: lluis.pujades@upc.es
[2] Geological Survey, Institut Cartogràfic de Cataluña, Barcelona, Spain.
E-mails: xgoula@icc.es; tsusagna@icc.es
[3] Applied Physics Department, University of Almería, Almeria, Spain.
E-mail: mnavarro@filabres.ual.es
[4] Instituto Geográfico Nacional. E-mail: jacanas@mfom.es

This work presents a contribution to the study of the modification of the seismic signal, from the rocky basement until the surface, in the city of Barcelona. The main purpose is to contribute a determination of the transfer function of the soils of the city, by the estimation of the predominant period. Barcelona is mostly located over sedimentary deposits. These sediments are heterogeneous in depth and also show important extreme conditions (see Fig. 1). There also exist outcrop rocks with different geotechnical characteristics, due to their origin and to several degrees of weathering.

In the fifties from the analysis of microtremor measurements in several thousand sites in Japan, it was found that these were useful to infer soil properties and to carry out earthquake-resistant designs.

KANAI and TANAKA (1961) found that distribution of microtremor periods depended on the type of subsoil. In the case of a simple stratified soil, a relatively sharp peak appeared around 0.1–0.6 s. On the other hand, when the formation of

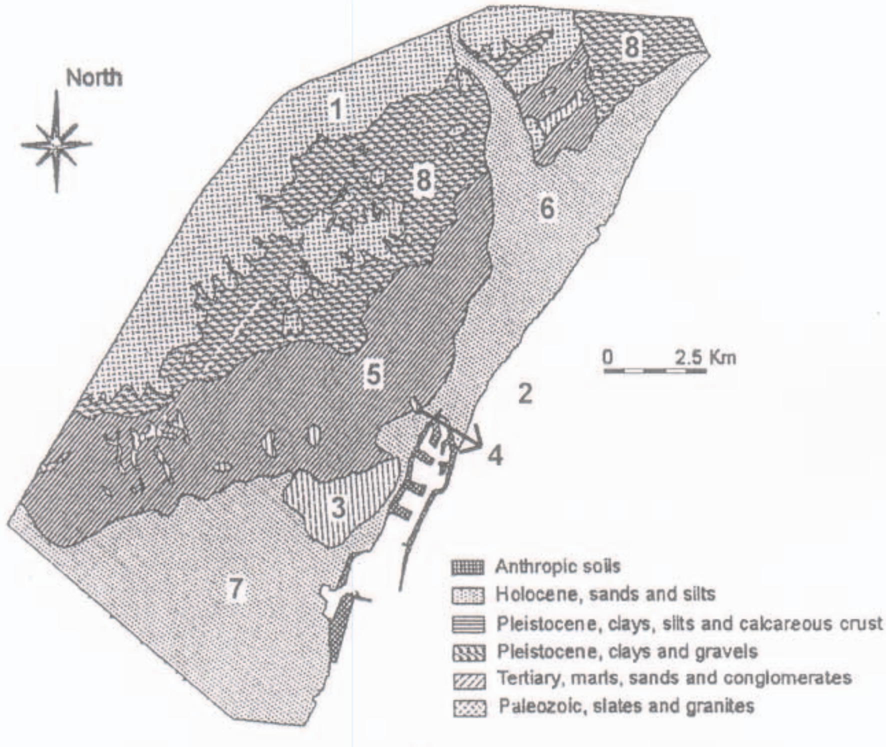

Figure 1
Geological map (GOULA *et al.*, 1998, modified from VENTAYOL *et al.*, 1978). Numbers correspond to the main geomorphic features of the city: 1) Tibidabo-Collserola mountains. 2) Mediterranean Sea. 3) Montjuic Hill. 4) Mount Taber. 5) Tricycle. 6) Besos river delta. 7) Llobregat river delta. 8) Torrential deposits.

soil was complex, more than two peaks may appear, one small near 0.2 s and one large near 1.0 s. On a mountain, a sharp peak appeared between periods 0.1–0.2 s, while on firm diluvial soil like that of uptown Tokyo this peak appeared between 0.2–0.4 s. On soft alluvial soils, such as downtown Tokyo, the curve was irregular in shape and a number of peaks appeared between 0.4–0.8 s. Additionally, on especially soft soils the curves were flat, varying the period between 0.05–0.1 s and 1.0–2.0 s. The period distribution curve is in many cases greatly influenced by the properties of the first layer. On the other hand, the curve in sound rock and those of the rocky basement were flat in the range of periods from 0.1 to 1.0 s.

KANAI and TANAKA (1961) concluded that the amplitudes of the microtremors at ground surface increase in those periods that are synchronized with the natural period of the subsoil because of selective resonance.

KANAI and TANAKA (1961) also carried out simultaneous observations of microtremors at several depths by using a self-leveling vibrograph (KANAI and TANAKA, 1958) in drillings performed in several types of soil. They concluded that: 1) the distribution of periods varies with the depth. 2) the variation of the distribution of amplitudes with the depth is not elemental nor formulable, and, 3) from the comparison of their results obtained from microtremors and those obtained from earthquakes, the recording of microtremors at the surface allows the same period of resonance, which is observed with the earthquakes, to be obtained. They present examples in which the distribution of periods for earthquakes and microtremors is compared, in which they conclude that the predominant period of a seismic movement is quite coherent with the most frequent period of the microtremors. Furthermore, in places in which the period distribution curves of microtremors has a single peak, this period clearly coincides with the predominant period found in the seismic movements. Finally, when the period distribution curve of microtremors has more than two peaks, the predominant period of the earthquake motions usually takes either of them and sometimes many of the peaks.

For the valuation of the predominant periods of the soil, the NAKAMURA method (1989) has been widely used. The approach and the hypothesis of Nakamura are summarized as follows:

– The horizontal tremor may be considered, to a certain accuracy, to be amplified through multi-reflection of the S wave while the vertical tremor is amplified through multi-reflection of the P wave.

– The effect of Rayleigh waves remarkably appears in the vertical tremor. Accordingly, the degree of its effect may be known by determining the ratio between the vertical tremor recorded at the surface and at the substrate. Namely, the effect of Rayleigh waves is nearly zero when the ratio is approximately "1". With an increasing ratio, the effect of Rayleigh wave may become more critical. Elimination of the effect of Rayleigh wave is obtained by using this ratio. Under two hypotheses: the surface layers do not amplify the vertical tremor and the effect of Rayleigh wave is equal for vertical and horizontal components. The transfer function ST = SHS/SHB, where SHS is the spectrum of the horizontal tremor on the surface, and SHB is the horizontal tremor spectrum of the incident from the substrate to surface layers, ST can be approached by RS = SHS/SVS obtained by microtremor measurements.

LACHET and BARD (1994) made numerical and theoretical investigations in order to analyze the possibilities and limitations of Nakamura's method. They observed at the position and the amplitude of the H/V peak. Regarding the position of the H/V peak, they studied its relation to the resonance frequency for different source types and for varied geological structures, and also compared the results with different types of incident waves. They concluded that the H/V ratios obtained for different source characteristics, all clearly exhibit a peak whose position is constant regardless of the source type and source function. In other words, for randomly distributed surface sources the H/V peak position is independent of the source characteristics. They also noted that Rayleigh waves are polarized in both horizontal and vertical directions, so that the peak observed in the H/V ratio may be related to the polarization curve of Rayleigh waves. Additionally, they compared polarization curves with H/V ratios calculated from noise simulation and they concluded that the shape of the H/V ratio is widely controlled by fundamental mode Rayleigh waves which, in turn, are closely related with the resonance phenomena. On the other hand, analyzing the variation of the SV waves with varying incidence angle and comparing with the polarization curves, they observed that the peaks generally correspond one by one to the higher resonance modes of the geological structure. However, these higher frequency peaks are not observed on the H/V ratios derived from noise simulation. They thought that this could be explained because the noise is composed not only of Rayleigh and SV waves but also of Love and SH waves.

For some years the Geological Survey of Catalonia, the Technical University of Catalonia (UPC) and other institutions have been working on a project in order to determine a Seismic Microzonation of the City. Field measurements and numerical simulations have been performed in order to assess the site effects. Preliminary numerical analyses were performed. SCHMIDT (1994) and FIGUERAS *et al.* (1995) evaluated predominant frequencies and amplification levels for five city sites by using 1-D linear method (KENNETT and STEWART, 1978) and 1-D equivalent linear technique (IDRISS and SUN, 1992). CID (1996) estimated the dynamic parameters of different layers from the static parameters deriving from boring data; BARCHIESI (1997) carried out sensitivity analysis on the frequencies and amplification levels of the soil, keeping in mind the dynamic values obtained by CID (1996). Finally GOULA *et al.* (1998) and CID *et al.* (1999) computed transfer functions characterizing different city zones.

Considerable preliminary work was also carried out to assess the soil response: LÓPEZ (1996) elaborated a code for the processing of the records by NAKAMURA's method (1989). This program was checked and supplemented by CHAVARRIA (1997). GUTIÉRREZ (1996) carried out measurements of microtremors in 19 sites within the city of Barcelona whose results are also included in this paper. From a geophysical point of view, LÁZARO *et al.* (1998) determined the depth of the Paleozoic basement from the analysis of 935 measurements of gravity anomalies.

Geological Setting

Following CANDELA (1983), the studied area is located in what is known as Barcelona plain, which is a coastal plain which extends between the Garraf massif to the West, and the counterforts of the coastal mountain range belonging to the district of El Maresme, to the east.

Their extension remains limited by the Tibidabo-Collserola Mountains to the northwest and the Mediterranean Sea to the southeast. The reliefs of the mountains are formed by Paleozoic material, with the presence of other outcropping in several districts of the city, such as Horta, Guinardó, Gracia, Sant Gervasi and Sarriá, forming elevations called "Turons." In a secondary term, the Neogene of marine facies of shallow waters can be observed in the Montjuïc hills (Miocene) and Mont Tàber, located downtown (Fig. 1).

The outcrop of Montjuïc consists of a series of layers of conglomerates and quartzite sands of cement silica, with intercalation of marl, sandy marl and loose sands. The thickness of these materials exceeds 200 m, as can be seen in the scarp of Montjuïc from the harbor. This outcrop has been widely exploited for material for construction (VENTAYOL *et al.*, 1978).

The quaternary materials are tricycle, torrential deposits of the streams and the deltas of the Besós and Llobregat rivers. The tricycle unit consists of calcareous crusts, yellowish limes with calcareous nodules and red clays (CANDELA, 1983).

The highest thickness of the tricycle is about 20 m; the thickness of the calcareous crust fluctuates between 2 m until it disappears in nodules. The origin and superposition of materials imply that the contact surfaces between them are not flat. Torrential deposits are more recent and they are located and joined over the tricycle materials. These deposits originating from the Tibidabo were dragged by the torrential courses. They have a thickness approaching 7 m, and are formed by heterogeneous materials (crust fragments, limestone nodules and angular rocks).

Finally, the Besós and Llobregat river deltas present a similar constitution. An impervious wedge (clays and limes), between two permeable formations (sands and gravels) constitutes them. Their thickness extends to about 70–80 m in the Llobregat river and 50 m in the Besós river (VENTAYOL *et al.*, 1978).

CID (1998) analyzed 70 geotechnical columns corresponding to 70 geotechnical soundings realized in the urban area of Barcelona and covering the layers between the surface and the Paleozoic basement, and characterized the shear velocities of the soils of the city. A 2000 m/s shear velocity was obtained for Paleozoic materials. Tertiary soils showed shear velocities of 1200 m/s, while quaternary materials, both Holocene and Pleistocene, are characterized by shear velocities less than 300 m/s.

Microtremor Measurements

The Nakamura method has been widely used for microzonation studies, such as e.g., Lisbon (TEVES-COSTA *et al.*, 1995; TEVES-COSTA and SENOS, 1996) and Basel (FÄH *et al.*, 1997). In order to map spatial variation of predominant periods of the soils in the urban area of Barcelona, noise measurements were performed.

As a preliminary step, two stability tests were performed. The purpose of these tests were: i) detect the presence of isolated sources of noise, which do not act during the entire day, ii) equipment problems, iii) problems in the processing of the records. The stability tests were made in outcrop rock and in soft soil sites.

These tests were conducted for a 24-hour period in the Fabra Observatory and on the campus of the Technical University of Catalonia UPC (NAVARRO *et al.*, 1997). Figures 2a and 2b present the results produced. No significant variations were found in the two test sites.

The noise measurements were accomplised with a high dynamic range accelerograph (Altus K2 of Kinemetrics), with a flat response up to 50 Hz and with a velocimeter prototype with a flat response between 2 and 10 Hz. 195 points covering the main features of the soils of Barcelona where selected. Microtremor measurements were recorded during 180 s, three times at each point, with a sampling rate of 100 samples per second. As noted before, special measurements (180 s, 24 times, one each hour) were performed in two specific sites for stability tests. Sensitivity test were also performed on the time window length selected for the data analysis; the results showed low dependence of the window length and, therefore, a high stability. Finally

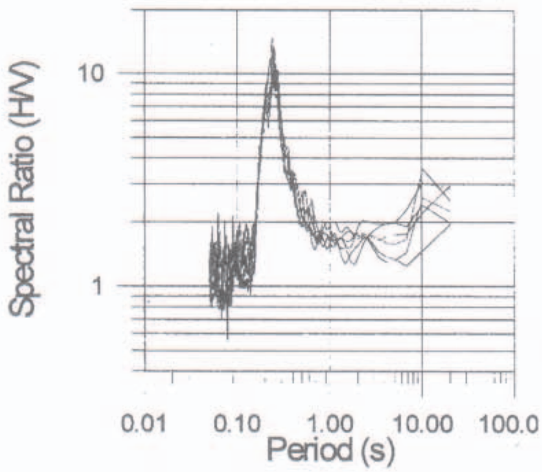

Figure 2a
Stability test in thin soft soil. Campus of the Technical University of Catalonia (UPC) (located west, over torrential deposits, see Figure 1).

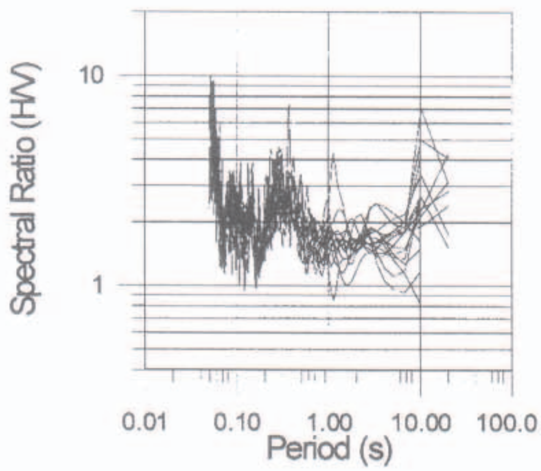

Figure 2b
Stability test in weathered outcrop rock. Fabra Observatory (located in Tibidabo-Collserola mountains, see Figure 1).

the following procedure was applied to the data records: 1) baseline correction, 2) band-pass filtering to retain the frequencies of interest, 3) 20 seconds time windows analysis using a Hanning window. A small overlap was used to avoid correlated residuals. 4) Spectral analysis and computations of H/V ratios. 5) Average results and 95% confidence intervals. Examples of spectral ratios obtained in the Llobregat delta river (thick soil deposits) and near Pedralbes (thin soil deposits) are shown in Figures 3 and 4, with the predominant periods estimated. The distribution of values of the predominant periods obtained in the totality of measurement is presented in Figure 5. Period range between 0.06 s and 2.0 s with a large number of values obtained near 0.06 s and 0.25 s.

Figure 6 maps the resultant predominant period's distribution. The predominant period for the Paleozoic outcrop rock of the Tibidabo and Collserola is quite homogeneous and presents a value of 0.06 s. This is probably due to the fact that it is not completely sound rock, but rather there exists a layer of weathered material (VENTAYOL *et al.*, 1978).

KANAI and TANAKA (1961) carried out microtremors measurement in a quarry of granite, on sound rock and on weathered rock. On the sound rock the curves of distribution of periods were flat, however in the weathered material a peak in a period of 0.06 s appeared.

The Quaternary material of the tricycle is the most heterogeneous of all. This is due to changes in thickness, which range between zero, in the base of the Tibidabo-Collserola Mountain and of Montjuïc and more than 20 m. There exists small zones with depths reaching 50 m. Also, the tricycle presents numerous creeks which extend from the mountains to the Mediterranean Sea. The obtained periods reflect this

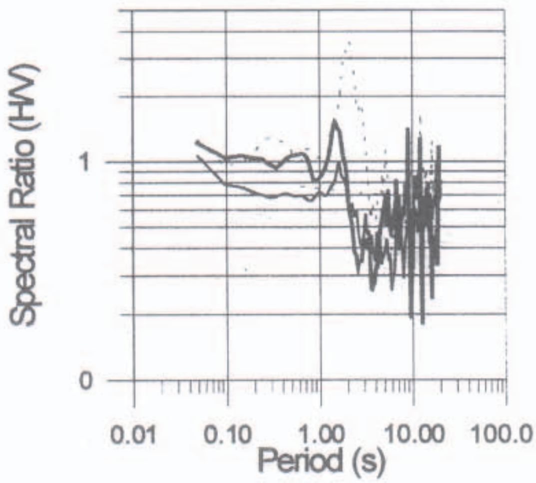

Figure 3
Examples of spectral ratio obtained in thick soil deposits of the Llobregat river delta.

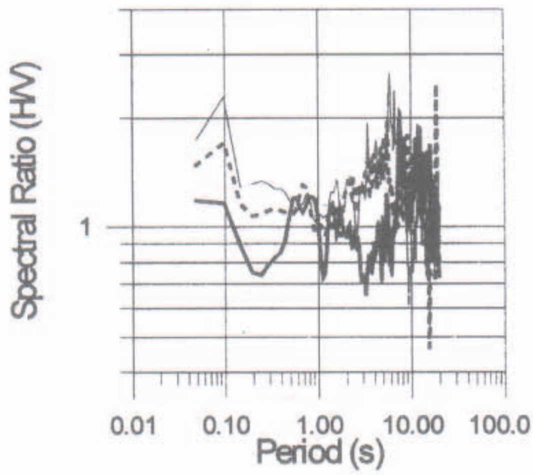

Figure 4
Examples of spectral ratio obtained in thin soil deposits near Pedralbes (located west, over thin torrential deposits, see Figure 1).

morphology, with values ranging between 0.10, 0.20, 0.30 s in the zones of high slope, to periods greater than 0.70 s up to 2.0 s in the majority of the Plain.

The materials of the Besós river delta present predominant periods exceeding 0.50 s, reaching the maximum value recorded of 2.0 s. It is possible to distinguish two zones: the first one following the course of the Besós with periods between 0.50 and 0.83 s and the second zone with periods between 1.0 and 2.0 s for the rest of the

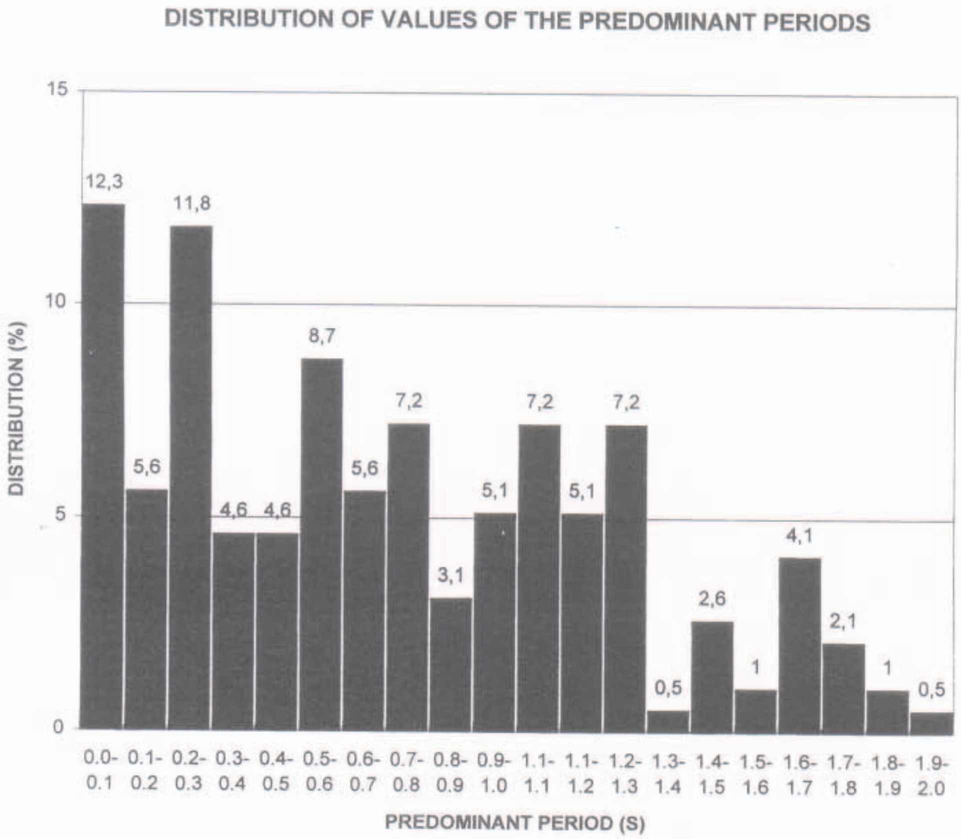

Figure 5
Distribution of values of the Barcelona soil's predominant period obtained by the Nakamura method.

deltaic material. However, there exists another subzone in the latter whose periods range from 0.67 to 0.91 s.

Finally, the Llobregat River delta zone yields homogeneous results, with a 0.72 s average period, and 0.77 s a constant value in 19 measurements (see Fig. 6).

Discussion and Conclusions

The objective of microzonation studies is to deal with the amplification and the predominant frequencies of the ground motion when an earthquake shakes it. The Nakamura method, due to its simplicity not only in the experimental tasks, but also in the data analysis, is a good alternative means to identify the soil predominant periods. In the case of Barcelona, the application of the method has enabled us to differentiate some zones.

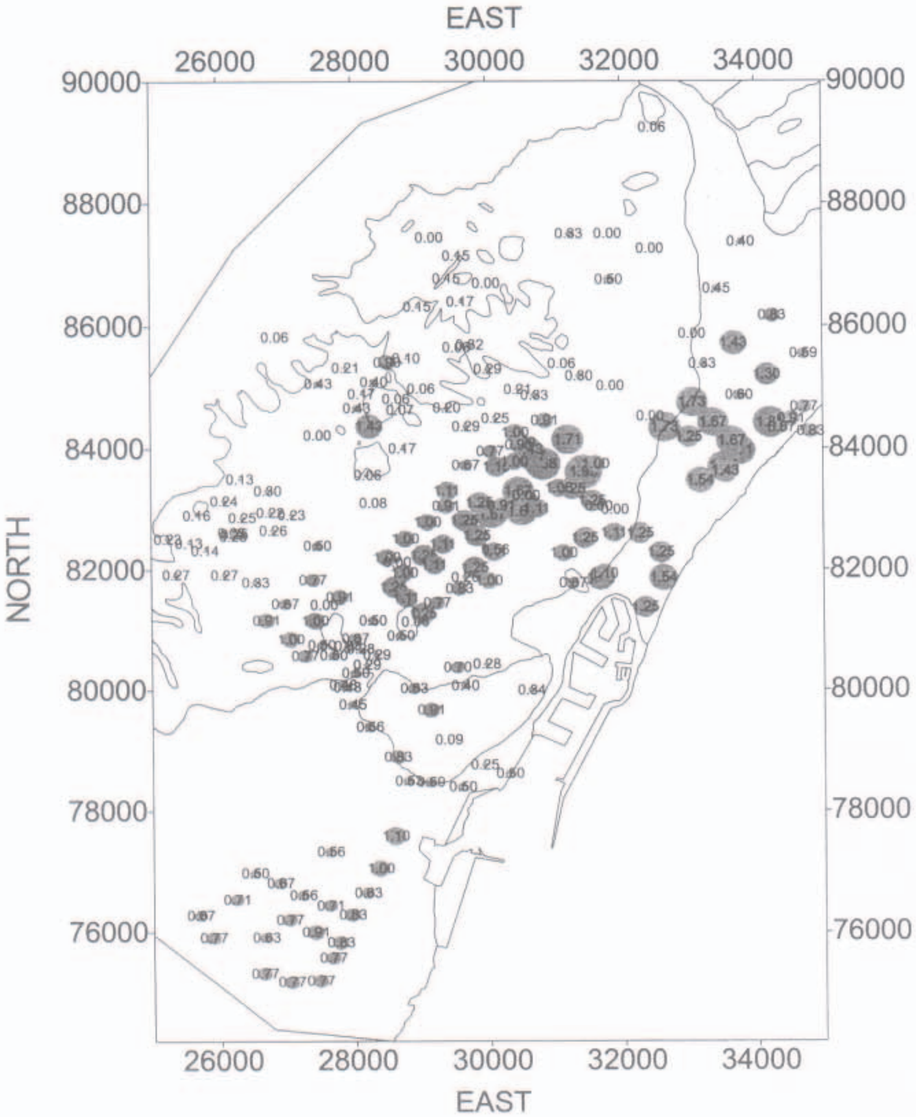

Figure 6
Soil's predominant periods of Barcelona.

The outcrop rock has different characteristics and the application of Nakamura's technique has reflected it. The variation of the period with the thickness of the material has been observed in the sedimentary deposits of the tricycle. The zone of the recent quaternary deltaic material of the Llobregat river is homogeneous. This differs from the analysis carried out in the right riverbank of the delta of the Besós river, which presents a heterogeneous behavior.

The determination of the soil predominant periods of the city of Barcelona using the method of NAKAMURA (1989) has allowed the classification of several types of behavior.

In the outcrop rock there are two types of behavior: a flat H/V curve and a flat H/V curve with a peak at 0.06 s (see Fig. 2b); behavior that could be due to the degree of weathering of the rock; in the first case we have healthy rock, while in the second weathered rock is found. KANAI and TANAKA (1961) reported this behavior for a quarry in the city of Tokyo. The Tertiary outcrop rock of Montjuïc presents, nevertheless, vast variability, which could be due to the multiple uses of this mountain over time: quarry, parks, etc. In spite of this difference, the base of the mountains of Tibidabo-Collserola and Montjuïc, both present predominant periods between 0.10 and 0.35 s (see Fig. 6).

The "Eixample" district is mainly located over "tricycle" materials. It presents periods higher than 0.70 s, with exceptions, which could be due to isolated variations within the underground, or due to the presence of artificial underground structures not anticipated and inventoried (ALFARO, 1997). Different underlying sediments of different thickness may also contribute to the observed behaviors.

The behavior of the predominant periods in the deltas of the Llobregat and Besós rivers is different. This difference could not be explained by the difference of the thickness of sediments. The delta of the Llobregat river is quite homogeneous and this fact is seen in the predominant periods; this delta suffered no important processes of sedimentation and erosion. Such is not the same for the delta of the Besós river, which manifests heterogeneity in the predominant periods. This condition can be due to the recent origin of the Besós delta, younger than 2,000 years, a status generated by the construction of the harbor works (CEHOPU, 1995). This recent origin and the urbanization of the zone imply several degrees of consolidation of the soil, and fillings with several physical and mechanical attributes.

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