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EXPECTED GROUND–RC BUILDING STRUCTURES RESONANCE PHENOMENA IN GRANADA CITY (SOUTHERN SPAIN)

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SUMMARY

The determination of seismic hazard, oriented to seismic risk management in urban areas, force us to know the resonance range between the dynamic behaviour of ground and the one of building structures. We developed a detailed study of dynamic behavior of RC building structures in Granada city. The main goals are to determine the empirical relationship between the fundamental period (T) and the number of stories (N) of RC buildings, by using ambient noise, and to calculate the damping factor by applying the Random Decrement Technique. Finally, we have obtained a probability map of expected resonance phenomena during future earthquakes.

INTRODUCTION

The softness of the surface ground and the thickness of surface sediments have been observed as two important local geological factors that affect the level of earthquake shaking. Their local variations can lead to spatial seismic intensity differences and may have a remarkable influence in building damage level and a significant earthquake damage distribution even in the cases of moderate earthquakes.

Since 1985 Michoacán, México earthquake, building damage have been studied analysing the contribution of site response, in particular when appears resonant phenomena. This strong influence of site effects on damage distribution has produced extreme consequences for example in the earthquakes of Leninakan, Armenia (1988), or Loma Prieta, California (1989). More recent destructive earthquakes (e.g. Northridge, California 1994; Kobe, Japan 1995; Izmit, Turkey 1999; Chi-Chi, Taiwan 1999 or Colima, Mexico 2003) have shown how unconsolidated soil and sediment deposits were responsible of important modifications in ground motion amplitude in a range of periods and how building damage increases when the fundamental vibration period of the building is the same that predominant period of the soil motion (Seo [1], [2]). For example, in the case of 17 August 1999 Izmit earthquake, the non uniformity in earthquake damage distribution indicates the local site effects associated with alluvial basins such as motion amplification and low-frequency enhancement, unfavourable to the structures of longer periods (Bakir et al. [3]).

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The relationship between soil amplification and level of damages has been confirmed recently for several large earthquakes ($M_w > 7.0$) and currently this dependence was analysed with regard to deep soil structures and tall buildings (e.g. Caracas, 1967 earthquake; México DF, 1985 earthquake or Kobe, 1995 earthquake). In some large earthquakes (e.g. Northridge or Kobe) have been proved that the pattern of peaks in ground acceleration and in ground velocity reflect the source proximity and rupture process, and we can find then significant directivity effects, nevertheless site effects are still very important and explain the ground motion amplification caused by surface geology and the degree of building destruction and his spatial distribution. Nowadays, it is thought that site effects are more significant for the lower shaking levels associated with small and moderate earthquakes, particularly at higher frequencies. Recent moderate destructive earthquakes on the region (Adra 1993, Balerma, 1994, Mula 1999 and Alhoceima, 2004), with maximum intensity observed in the epicenter areas of VII or VIII on the EMS (1998), have shown that damage distribution is generally related to the typology of soil and the dynamic behavior of buildings, noticing large differences at the level of damages for relatively short distances (Navarro et al. [4], [5]). For this reason, in regions of moderate and small earthquakes, to analyse local site effects have an especial relevance.

In order to evaluate seismic risk of Granada city, various research works for seismic microzoning have been carried out as an activity in the Spanish-Japanese joint research on seismic microzonation in basin areas since 1990. This joint research includes microtremor array measurements to evaluate the deeper underground structure (Seo [6]), mobile microtremor measurements to know the distribution of predominant period of the surface ground (Morales et al. [7]; Vidal et al. [8]; Cheddadi [9]), S-wave velocity prospecting tests to obtain the shear velocity models of near surface ground (Seo [6]) and microtremor measurements on building structures to evaluate their dynamic behavior (Kobayashi et al. [10], Navarro et al. [11]). Some research studies realized on other parts of the world, have shown that the determination of natural period of building using microtremor measurements is a quick, efficient and economic method. It is based on the principle that microtremor propagates on the building and is amplified at periods which are synchronous with the natural period of building. Among the works we mention Kobayashi et al. [12] in Mexico city; Midorikawa [13] in Santiago de Chile and Viña del Mar; Enomoto et al. [14] in Caracas (Venezuela); Oliveira et al. [15] in Lisboa (Portugal).

The main goal of this work is to estimate the expected ground-RC building structures resonance phenomena in Granada city during future earthquakes, taking into account the predominant period of soil obtained from Nagoshi-Nakamura method and the dynamic behaviour characteristics of RC building structures using microtremor measurements in both cases. Furthermore, the constitution of a data bank of predominant period of soils, natural period and damping factor of existing buildings has been useful not only to evaluate the dynamic behavior of buildings in Granada urban area, but also for quantitative and prompt damage evaluation of buildings after an earthquake, because the change of the natural period and damping factor before and after the earthquake is related with stiffness degradation of structural elements of the building.

GEOLOGICAL SETTING

Granada city is located in Granada basin (Andalusian region, southern Spain (Fig. 1)), which is one of the largest Neogene basins of the Betic range. This range is a part of the Betic-Riff region, which is the western end of the Perimediterranean Alpyne System. The formation of the Betic range is the result of an intracontinental collision between the Eurasian and African plates occurred from the Cretaceous to the Neogene ages. The convergence between Africa and Eurasia is the responsible of the recent tectonic and seismic activity, and this convergence has caused important extrusion motions to the southwest of the Betic. The approach of those plates and consequently their deformation continued during the Neogene and the Quaternary generating an intramountain Neogene basin. The formation of the Granada Basin started in the Middle Miocene, although it is from the late Miocene to the present that it acquired its principal features.

Figure 1. Geographical location of research area (Granada city, southern Spain)

The co-existence of compressional and extensional tectonics complicates the understanding of the collision, and many aspects of the tectonic structure and the development of the region are still a matter of debate. The release of seismic energy creates a diffuses seismic pattern in this plate boundary and consequently the seismicity band in a longitude range (0º E – 6º W) may reach more than 400 km broad between the Iberian and African limits (Morales et al. [16]). The seismicity of the Betic region is characterized by a high microearthquake and small earthquakes activity (Figure 2). Moderate earthquake are less frequent in the region and currently occur in certain specific nucleus (some of then in the Granada basin).

The zone under study is, from the point of view of seismic activity, the most hazardous region in Spain. Granada is the main city in the region where a big earthquake can cause the most serious damage to buildings and urban facilities. Historical seismicity data (Vidal [17]; Espinar and Morcillo [18]) reveal that Granada city has a medium or medium-high level of seismic hazard (Figure 2) and, in the past, some big near earthquakes (e.g. 1431, 1806, 1884) occurred around it and many buildings and urban facilities were completely destroyed in the zone. The earthquake activity in Granada basin is shallow with the exception of the very deep 1954 earthquake, with $M_w = 7.9$. Therefore, we must do our best to prevent the effects of large earthquake from shaking this area.

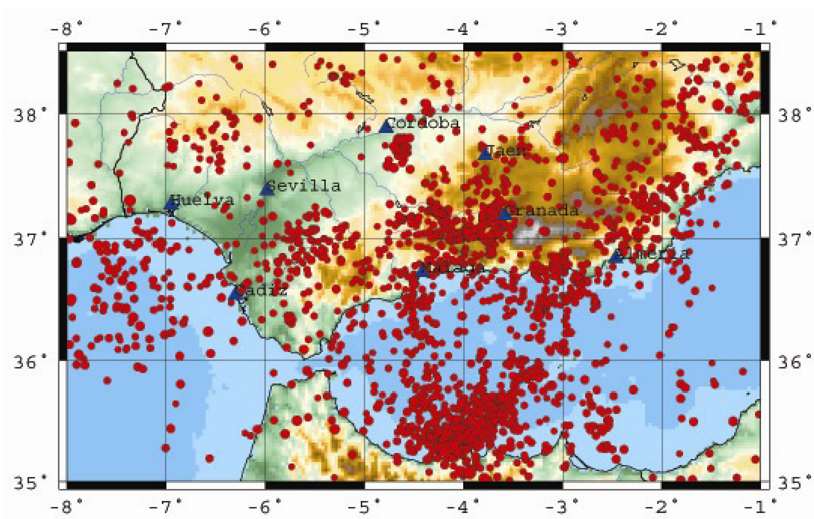

Figure 2. Seismicity of Andalusia–Alboran sea region for the period 1984-2004 ($M \geq 3$) taken from IAGPDS Data file.

Geologically speaking, the Granada basin is bound to the north and west by subbetic domain materials and to the south and east by Alpujarride metamorphic units of the Alboran domain (Sanz de Galdeano [19]). Based on analysis and interpretation of gravimetric and seismic reflection data, four principal troughs of different depth have been found in the basin (Morales et al. [20]). These structures are filled with Neogene-Quaternary sediments that reach a thickness of about 3 km.

We performed an analysis on landforms and geological conditions in the Granada city and surrounding areas in order to divide the research area into several units where is expected a different ground seismic response. A landform classification map was developed with analysis of aerial photograph and topographic map with a 1:10000 scale, surface geological conditions and S-wave velocities for the top and last layers obtained from shallow seismic refraction surveys. The four main units of the research area are: recent alluvium, old alluvium, clay containing gravel and Alhambra formation (Figure 3). Geological condition of each unit is lined from the younger to the older. The Alhambra formation composing the oldest unit is deposited during the late Pliocene and early Pleistocene. The average S-wave velocity for the top layer of each unit is 160 m/s, 200 m/s, 220 m/s and 440 m/s, and for the last layer is 470 m/s, 510 m/s, 405 m/s and 1060 m/s respectively. We rearranged the S-wave velocity obtained before (Seo [6]) for each landform unit (Table 1).

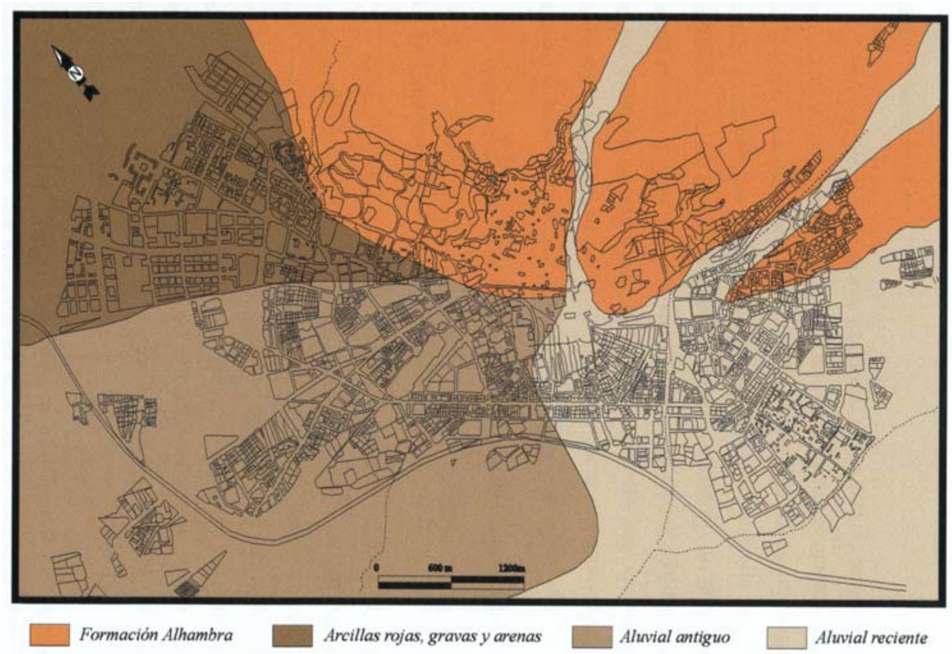

Figure 3. Landform classification map in Granada city as appear in the GIS on earthquake damage scenarios management.

Table 1. S-wave velocity range for each landform unit (m/s) (Seo [6])

Landform unit	Number of data	Top layer	Last layer
Alhambra formation	5	376 – 617	625 – 1818
Upper alluvial fan	5	125 – 330	331 – 847
Lower alluvial fan	13	107 – 294	425 – 625

DYNAMIC BEHAVIOUR OF RC BUILDINGS

The microtremor measurements in the buildings of Granada city were carried out during May, 2001. They were performed at the top of the buildings, using a data acquisition system composed by a three component short period seismometer with natural period of 1 sec, amplifier and notebook computer with A/D converter. The system was used to record the horizontal and vertical components of microtremor at the top of the buildings. The first channel was adjusted to the longitudinal direction, the second one to the transverse direction and the third to the vertical direction, respectively. The signals were amplified depending on the characteristics of each site, and after being integrated, the signal proportional to displacement was directly recorded on a lap-top personal computer. At each observational point a time history 180s long of microtremor signal was recorded, sampled at a rate of 100 samples per sec.

The structural vibration measurements of building structures in Granada city were performed at the center of plan on the roof floor or at the last story of buildings. The displacement of the structure was measured, and Fast Fourier Transformation was applied to every record in order to compute Fourier spectrum, smoothening with a Parzen's window of 0.3 Hz width (Figure. 4). The total number of buildings evaluated was 89, 78 private buildings and 11 public buildings with number of stories between 3 and 16. The dominant type of construction in Granada City consists in reinforced concrete frames with unidirectional floors composed of reinforced concrete joists and ceramic arches, exterior brick walls without earthquakes-resistant design, formed by cavity wall with thermic isolation, and also reinforced concrete foundation formed by clamped footings. In general, the criterions to select the investigated buildings were the regularity both in plant and elevation.

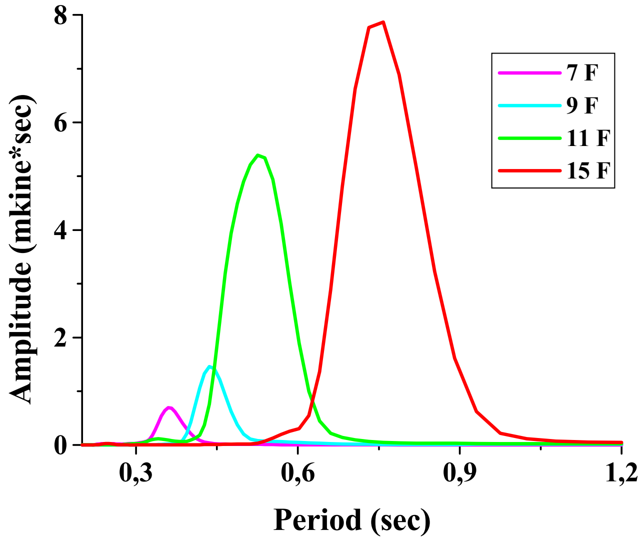

Figure 4. Examples of amplitude Fourier spectrum of longitudinal component for several buildings with 7, 9 11 and 15 stories.

The results show that the natural period of buildings increases with the number of stories, which is in agreement with the results provided by several authors (Kobayashi et al. [12]; Kobayashi et al. [10]; Midorikawa [13]; Enomoto et al. [14]) using microtremor measurements. The lowest value of T is 0.16 sec, and it corresponds to buildings with number of stories N = 3. The highest values of T is 0.89 sec for buildings with number stories N = 16. The value range of standard deviation band is between 0.03 and 0.09 sec. The relationship between the natural period and the number stories N is $T = (0.049 \pm 0.001)\ N$ for swaying motion (Figure 5) with a correlation factor r = 0.98, showing a clear linearity between both parameters.

In comparison with other similar works, the result obtained in this study exhibits a very good agreement with the relationships obtained from microtremor measurements performed in Granada, in 1994: T = 0.051N (Kobayashi, et al., 1996), in Almeria, Spain: T = 0.048N (Enomoto et al. [21]) and

Santiago de Chile, Chile: T = 0.049N (Midorikawa [13]). It is slightly larger than the relationship obtained in Barcelona, Spain, for reinforced concrete buildings: T = 0.046N – 0.048 (Espinoza [22]) and smaller than the relationship obtained in Caracas, Venezuela: T = 0.06N (Enomoto et al. [14]) and Tokyo, Japan: T = 0.06N and is much smaller than the relationship obtained for Mexico: T = 0.105N (Kobayashi et al. [12]).

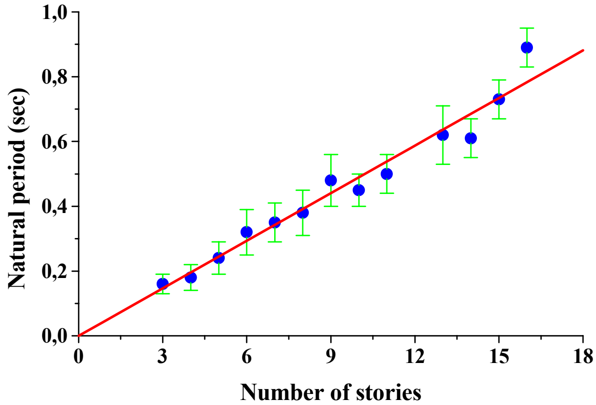

Figure 5. Relationship between the natural period and number of stories for swaying motion. The vertical bars show the standard deviation for each period.

Random Decrement Technique (Tamura et al. [23]) was applied using microtremor measurements to evaluate directly the damping factor of building structures in 89 RC buildings of Granada city. This technique is very useful to evaluate the damping factor of actual buildings under random excitations and it requires simple equipment and instrumentation. From microtremor record at the top of each building, we have obtained the free vibration response for underdamped building by means of superposition of samples, and we determined the damping factor from the ratio of two displacement amplitudes measured at an interval of m cycles. An example of this method of evaluating the damping factor is illustrated in Figure 6, for a building with 7 stories (T = 0.36 sec), located in the urban area of Granada city.

The value range of damping factor for longitudinal component is from 1.5% to 12.5% and the average value is 5.8% with standard deviation 2.3%. The transversal component shows the values range of damping factor between 1.9% and 11.8%, and the damping factor average value for this component is 5.9±2.4%. In general, the result of damping factor mean value for each number of stories shows high standard deviation. However, the damping factor values range for buildings with the same typology (material, construction age, founding type, number of stories and dimension), located in the same soil conditions, exhibits very low standard deviation.

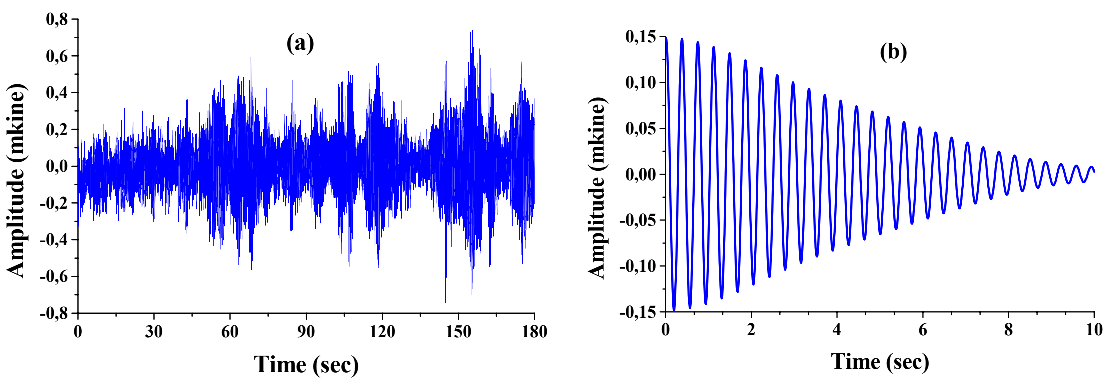

Figure 6. Example of evaluation of damping factor. (a) trace of unfiltered microtremor measurement; (b) response of underdamped building.

According to a previous research (Kobayashi [24]; Midorikawa [13]), the damping factor is inversely proportional to the natural period, and the product of both parameters could be considered almost constant for buildings located on soils with same typology, being hT value larger for buildings on soft ground than on hard ground. The relationship between the damping factor and the natural period for the swaying motion in Granada city (Figure 7) is not clear. This fact can be due to the different soil conditions present in the urban area of Granada city, and it suggests that the damping factor of buildings would be strongly affected by energy dissipation between soil and structure.

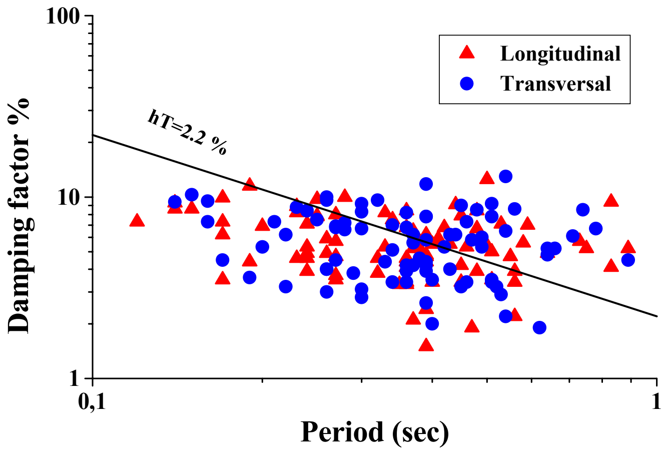

Figure 7. Relationship between natural period and damping factor for swaying motion.

The hT values range for longitudinal component between 0.58% and 7.8%, being the hT average value for this component 2.12% with standard deviation 1.21%. The transversal component shows hT values range from 0.67% to 8.97%, and the average value for this component is 2.22±1.42%. According to these results, the average value for swaying motion in Granada city is estimated as hT = 2.2±1.3%. This result is higher than the results obtained in Tokyo (hT = 1.5%) and Santiago de Chile (hT = 0.8%), and it is smaller than the value obtained in Mexico city (hT = 4.0%). These differences could be caused by the different soil conditions in each region.

PROBABLE GROUND-RC BUILDINGS RESONANCE PHENOMENA

Resonance phenomena has been recently observed in southeastern Spain in the Mula earthquake (Navarro et al. [4]) and Adra earthquake (Sanchez et al. [25]). In order to obtain the probable resonance phenomena in Granada city we have compared predominant period of soil and fundamental period of building structures.

The ground microtremor measurements were performed in the urban area of Granada city with a 200 m x 200 m grid. Because microtremor spectra can be affected by near sources, as machinery, special care were taken to work as far as possible of close disturbances such as cars, heavy machinery facilities, household appliances, etc. The Nakamura´s technique was applied obtaining the predominant period at each site (Vidal et al. [8]; Cheddadi [9]) (Figure 8).

We have collected building height data and we have estimated the natural period of building from the period-number of stories relationship. After that, we compared this theoretical period of buildings with predominant period of soil in the building site. When both periods are in agreement we consider that resonance effect is probable, and we have plotted these buildings in a resonance map (Figure 9).

All data mentioned above: geomorphological, S-wave velocity, predominant period of soil, natural period of buildings and resonance effect have been georefered and implemented in a GIS of earthquake damage scenarios management that is operative in the Andalusian Institute of Geophysics (IAG).

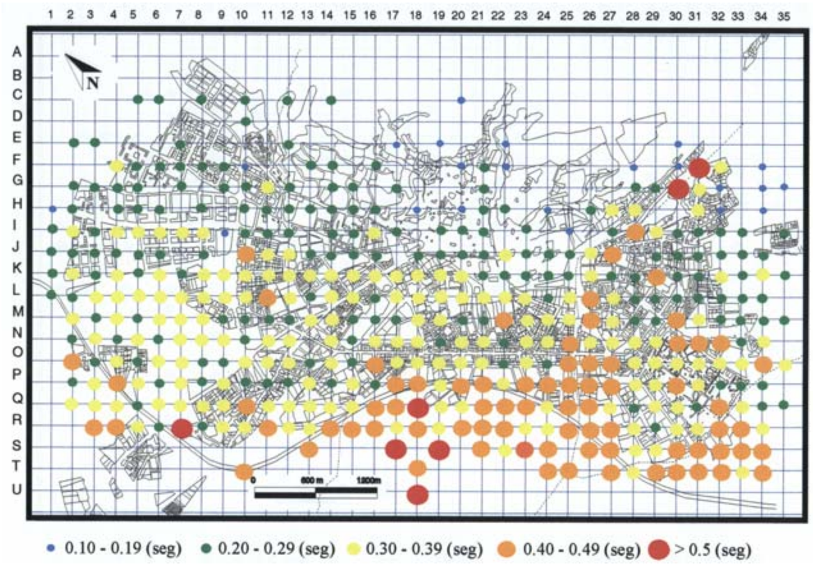

Figure 8. Predominant period distribution map in Granada city from microtremor data analysis.

CONCLUSIONS

Assuming that there is no systematic differences in building design or construction practice among different RC buildings in Granada city and consequently the natural period is a lineal function of number of stories, we have intended to find those where probably could appear resonance phenomena in future earthquakes. We have assumed also that ground motion during moderate earthquake is into lineal behaviour and predominant period of soil obtained with microtremor is the more relevant part of ground response.

The analysis of geomorphological and seismological data has allowed us to define four main units grouping different general characteristics of ground motion. The predominant period of soil obtained with Nakamura's method shows significant features of ground motion in a more detailed way, and in agreement with the surface geological conditions.

The clear relationship between the natural period of RC buildings and the number of stories T = 0.049 N, similar to does obtained in another cities in southeaster Spain, allow as to estimate the natural period of all RC buildings in Granada city applying this relationship.

The damping factor has been evaluated by applying the Random Decrement Technique. The damping factor average value for swaying motion is 5.9±2.4%. The relation between damping factor and the natural period is not clear, and the values range of the product between damping factor and natural period exhibits large fluctuation, being estimated the average value for swaying motion in Granada city as hT = 2.2±1.3%. This result is different compared with the results obtained in other cities by using microtremors. These differences could be caused by the different structural typologies and different soil conditions in each region.

The map of probable resonance phenomena in Granada city, comparing predominant period of soil and natural period of RC buildings, shows that a significant number of buildings be able to have dominant periods close to the ground motion ones and consequently resonant phenomena would be able to appear if an earthquake occur in the zone.

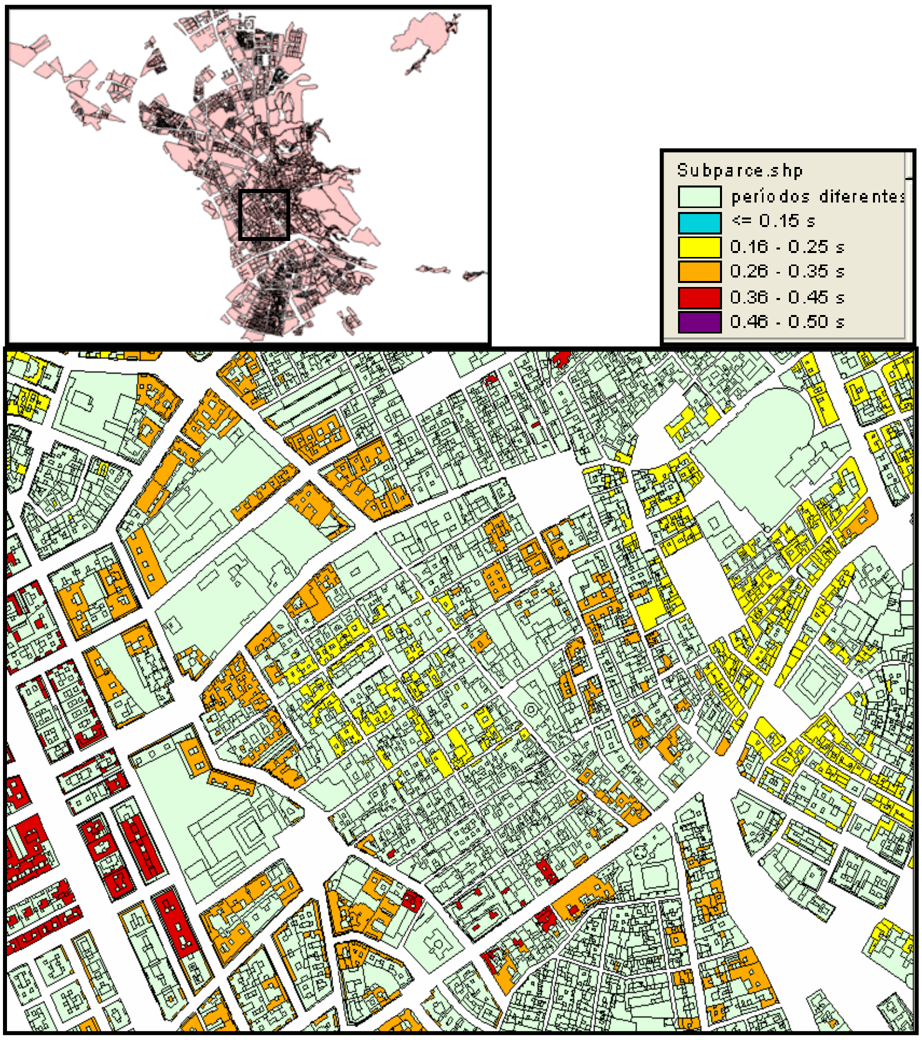

Figure 9. Distribution of expected resonance effect in RC buildings in a zone of Granada city shown in the general map in the left upper part of the figure. Green colour means no probable resonance phenomena.

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