Analysis of site effects, building response and damage distribution observed due the 2011 Lorca, Spain, Earthquake.

M. Navarro & A. García-Jerez
University of Almeria, Almeria & IAGPDS, University of Granada, Spain.

F.J. Alcalá
Geo-Systems Centre (CVRM-IST), Technical University of Lisbon, 1049-001 Lisbon, Portugal.

F. Vidal & C. Aranda
Andalusian Institute of Geophysics, University of Granada, Granada, Spain.

T. Enomoto
Department of Building Engineering, University of Kanagawa, Yokohama, Japan.

SUMMARY:
The shallow geology of Lorca town (Murcia, southeast Spain) was classified from a new-performed geological cartography (1:10.000 scale), geotechnical data, and geophysical surveys. Unconsolidated geological materials were clustered in terms of the shear-wave velocity structure evaluated by means of the inversion of Rayleigh wave dispersion data obtained from vertical-component array records of ambient noise. Ambient vibration records were performed at 82 observation points and the Horizontal-to-Vertical Spectral Ratio was calculated to determine a predominant period distribution map. Ambient noise measurements at the top of 48 buildings (2-12 stories high) was carried our in order to investigate the empirical relationship between the fundamental natural period and the number of stories, and also to estimate the damping factor in the range of small amplitudes. Finally, we examined the reliability of this study for explaining the damage distribution caused by the May 11th, 2011 Lorca destructive earthquake (Mw = 5.2).

Keywords: geological classification; site effects; dynamic behaviour of RC buildings; Lorca earthquake.

1. INTRODUCTION

Lorca town is located in Murcia province (SE Spain), belonging to the eastern part of the Betic Cordillera (Figure 1). This is the most hazardous seismic region of Spain, characterized by frequent earthquakes of small and moderate magnitude (generally smaller than 5.5), although most of the largest and destructive historical earthquakes occurred during the last six centuries in Spain took place in this area (Vidal, 1986). Recently, three earthquakes have occurred in 1999 (Mula), 2002 (Bullas), and 2005 (La Paca) near Lorca town with magnitudes (Mw) of 4.7, 5.0, and 4.8, respectively, and epicentral macroseismic intensities ranging from VI to VII (EMS scale). These events have shown the special relevance of site effects for explanation of both the ground motion amplification caused by shallow geology, and the degree and spatial distribution of building destruction (Navarro *et al.* 2000; Benito *et al.* 2006).

During the course of the present research, two new shallow quakes occurred on May 11th, 2011 with epicentre near Lorca town (Mw = 4.6 and 5.2, respectively). The mainshock of the Lorca seismic series occurred on May 11th at 16:47 UTC (18:47 local time), with epicentral distance of 5.5 km from the city center and shallow hypocenter (4.6 km deep). Peak ground acceleration (PGA) of 0.37 g and peak ground velocity (PGV) of 35.4 cm/s were observed at the Instituto Geográfico Nacional (IGN, 2011; www.ign.es) Lorca strong-motion station. The maximum macroseismic intensity was initially estimated as VII (EMS scale) by the IGN and the Instituto Andaluz de Geofísica (IAG, 2011; www.ugr.es/~iag), highlighting again the influence of the earthquake ground response on building behaviour during the shaking. There were damaged buildings in all districts of the town, but the levels and percentages were fundamentally different depending on building vulnerability and ground motion characteristics. The most severe damage appears in La Viña (southwestern zone) and La Alberca and La Alameda districts (close to the Guadalentin River) as shown in Figure 2.

Site effects sometimes explain ground motion amplifications found in narrow high-frequency bands which may have severe effects on the degree of building destruction and spatial distribution. An example of that was found in Villa de Alvarez town (Mexico) due to the 2003 Colima earthquake. Variation in the ground behaviour was clearly observed attending to the ambient noise H/V spectral ratio at damaged and undamaged zones. Clear spectral peaks were found in a short period range between 0.1 and 0.2 s in the heavily damaged zone, whereas these peaks did not appear at the undamaged sites (Enomoto *et al.* 2004, Navarro *et al.* 2008).

The December 23rd, 1993 and the January 4th, 1994 Adra earthquakes, are examples of amplification due to site effects in small events. The most relevant damage in Adra town occurred in reinforced concrete (RC) buildings of four or five storeys placed on alluvial deposits of around 30-m thick with a predominant ground period of around 0.2 s (Navarro *et al.* 2007). Influence of resonance phenomena is also suspected in the case of the February 2nd, 1999 Mula earthquake. RC structures with four and five stories located in the central-western part of Mula town had more serious damage than those located in other parts of the town during that quake. Thus, site effects caused by the shallow ground structure (García-Jerez *et al.* 2007) and resonance phenomena between shallow geology and building probably had strong influence on the damage distribution for RC buildings.

The main goals of this work are: i) to analyze the local site effects in Lorca town from the shallow S-wave velocity structure of the ground in terms of predominant periods; and ii) to estimate the fundamental translational periods and damping ratios of a large set of existing RC-framed buildings before and after Lorca 2011 earthquake sequence. Period elongation after strong ground shaking and its relation with damage level suffered by this subset of structures were investigated.

2. GEOLOGICAL SETTING

Lorca town belongs to the eastern part of the Alpine Betic Chain, in southeast Spain (Figure 1). The identification and classification of its urban geology was a step to perform a new geological cartography at scale 1:10.000 (Figure 1) and to interpret the geometry and spatial continuity of geological formations. The dataset gathered from bibliography consisted on 14 field-ground testing data, geotechnical tests: 40 mechanical drillings and geotechnical parameters, and geophysics surveys: 27 electrical geophysical tests and 10 shallow refraction profiles with 10-50-m penetrating thickness from the Instituto Geológico y Minero de España (IGME, 1992). These data allows for the mechanical properties of geological formations to be clustered and correlated according to the specifics elements for geological correlation in urban areas described by Alcalá *et al*. (2002).

Five main geological-seismic formations were clustered in Lorca town by combining the geological, geotechnical and geophysical information of the 17 geological formations identified in the field (Figure 1): (1) Palaeozoic to Triassic pre-orogenic metamorphosed hard-rock (bedrock), which includes schists, phyllite, quartzite, and dolomitic limestone from the Alpujárride and Maláguide Complexes; (2) lower to upper Tortonian pre-orogenic medium-hard bedrock, which includes conglomerates, marls, gypsum, sandstones and Pliocene consolidated glacis; (3) Pleistocene unconsolidated glacis and colluvials; (4) Holocene unconsolidated colluvials and alluvial terraces; (5) croplands and anthropogenic fillings. The basement (bedrock) was defined as "medium-hard" for Neogene materials and "hardest" for pre-Triassic materials. Both types of bedrocks outcrop at northern and western areas of the town, being prospected from between 10 and 50 m depth in the centre of Lorca town and from more than 100 m at southeast. Complementary details on the shallow geology classification of Lorca town can be found in Alcalá *et al*. (2012).

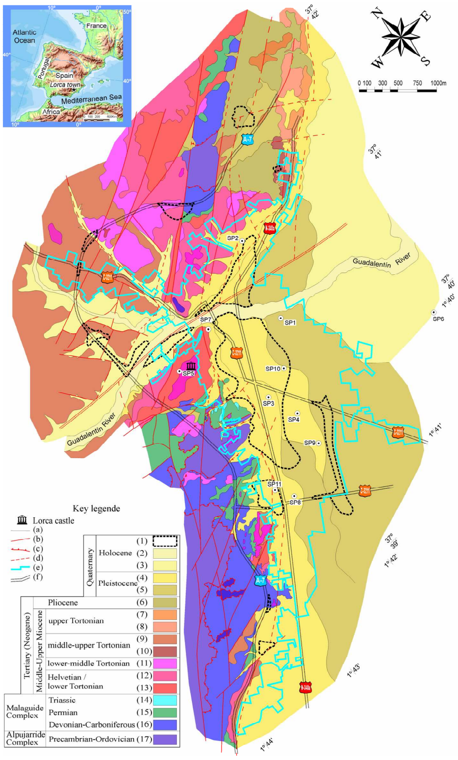

Figure 1. Geological cartography of Lorca town at scale 1:10.000. (a) undifferentiated geological contact; (b) normal fault; (c) thrust fault; (d) inferred fault; (e) urban boundary (blue bold line); (f) main roads. Array locations have been labelled from SP1 to SP11.

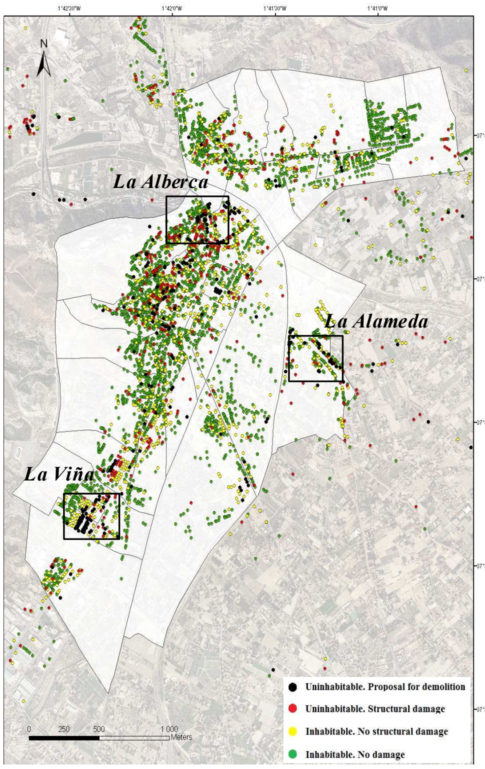

Figure 2. Damage distribution in Lorca town due May 11th, 2011 Lorca earthquake.

3 ANALYSIS AND RESULTS OF AMBIENT NOISE RECORDS

3.1 Shear-wave Velocity Structure

Since the NEHRP soil classification in 1994, the mean shear-wave velocity in the first 30 m (V_S^{30}) has been adopted as a representative site characteristic parameter in several official seismic codes (e.g. NCSE-02; Eurocode-8 (EC8)). The spatial autocorrelation method (SPAC method, Aki, 1957) and its related techniques of ambient noise analysis (e.g., García-Jerez *et al.* 2008; 2010) have been proved as innovative and convenient ways for determining the elastic properties of shallow sedimentary deposits in this kind of studies (e.g., Parolai *et al*. 2005; García-Jerez *et al*. 2008).

The shallow geological structure of Lorca town has been studied using a Spatial Autocorrelation method (SPAC). The measurements were carried out at eleven open spaces (Figure 1), called hereafter SP sites. Vertical components of soil motion, excited by ambient noise, were recorded using circular-shaped arrays. We used different radii depending on the thickness of geological formations deduced from geological and geophysical data and on the dimensions of the open areas. The radii ranged 3-to-50 m. In order to obtain the correlation coefficient $\rho(f,R)$, the cross-correlations between records on the circle and the central station were calculated in frequency domain and divided by the autocorrelation at the center (Figure 3a), and the phase-velocity of the Rg-wave was computed for each frequency f from the relation $\rho(f,R)=J_0(kR)$, where k stands for wavenumber and J_0 is the zero-order Bessel function (Figure 3b). The frequencies of the obtained dispersion curves ranged from 2.9 to 24.0 Hz and the phase velocity values varied between 184 and 749 m/sec.

Rg-wave phase velocities have been inverted in order to obtain shear-wave velocities (Figure 3c). Because of the important differences among the dispersion curves, both in frequency and in phase velocities, the number of layers and the ranges for thicknesses and shear velocities were different for each site. Finally, the average shear-wave velocity of the upper 30 m (V_S^{30}) was computed and soil classification map of Lorca town based on the V_S^{30} distribution has been obtained (Figure 4), according with Eurocode EC8 (1998).

3.2 Predominant Period of Soil

The measurements of ambient vibration in Lorca town were performed during March 2004 and complemented in June 2011 to evaluate the resonant period of the shallow geology. Three-component ambient vibrations were recorded at 82 sites of a grid with 400m x 400m cells. Fourier spectra were calculated at each point for several time windows free of artificial disturbances and Nakamura´s method (Nakamura, 1989) was applied, obtaining the predominant period of each site (Figure 3d).

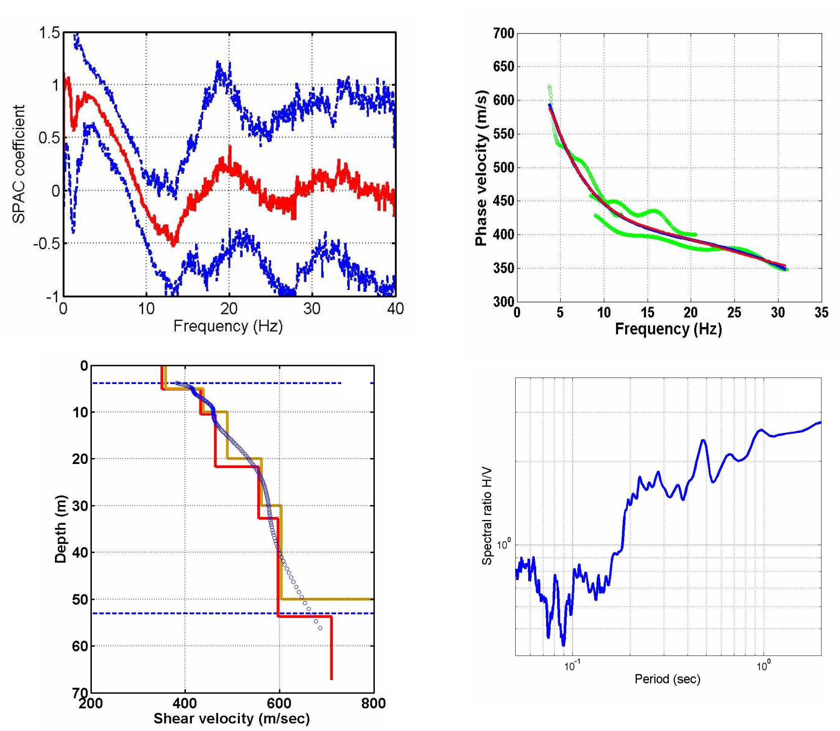

Figure 3. Some results obtained at La Viña area: (a) SPAC coefficient for a radius of 20 m; (b) Smoothed fundamental-mode Rg dispersion curve (blue colour), theoretical dispersion curve (red color) obtained from Shear-wave velocity model and dispersion curves for radius: 5, 10 and 20 m (green colour) ; (c) Shear-wave velocity model (red colour) derived from inversion of phase velocities, initial model represented by yellow colour, and blue circles represent the S-wave velocity values obtained from the $\lambda/3$ criterion (e. g. Tokimatsu, 1997); (d) H/V spectral ratio.

The spatial distribution of predominant periods (Figure 5) reveals a general increasing trend from 0.1-0.3 s in northern and western bedrock areas to 0.3-1.0 s towards the central and eastern zones, where unconsolidated Quaternary formations of variable thickness – usually increasing towards the southeast

– outcrop. These later areas exhibit considerable lateral variability in terms of HVSR shape. Moreover, multiply peaked HVSR are often found, with the predominant peak depending on the local impedance contrasts. These characteristics reflect the complexity of the local shallow geology structure.

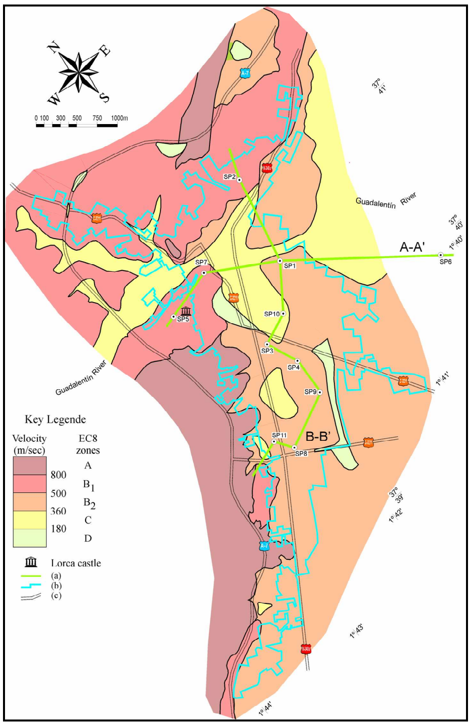

Figure 4. Ground classification of Lorca town based on the average shear-wave velocity distribution down to 30 m (V_S^{30} in m/sec), according with Eurocode EC8 (1998).

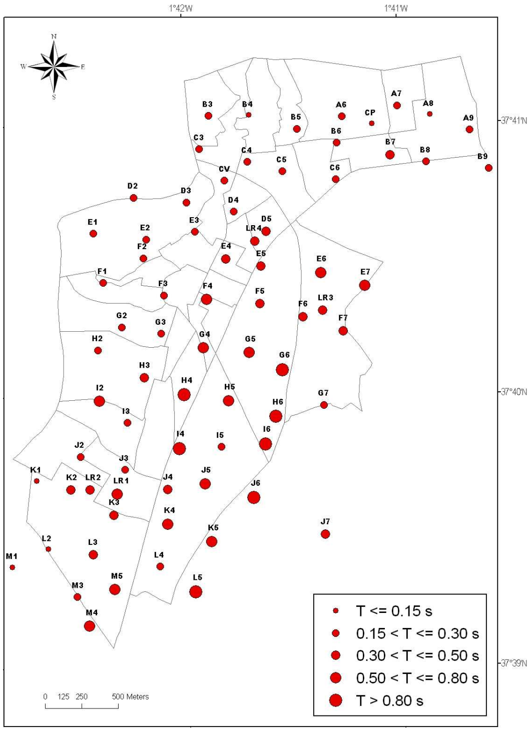

Figure 5. Predominant period distribution map at Lorca town.

3.3 Dynamic Properties of Existing RC buildings

The measurements of ambient vibration were performed in Lorca and Mula towns in March 2005 and complemented in June 2011 to evaluate the dynamic characteristics (fundamental period, T, and damping ratio, h) of RC-framed existing buildings and to estimate variations of these dynamic parameters comparing pre- and post-earthquake measurements at the same buildings. Before the earthquake sequence, the total number of measured buildings was 59, with a number of storeys ranging from 2 to 12, 44 of them located in Lorca town. After the earthquake, 34 of them were measured again using the same methodology. For all buildings we determined the fundamental period and damping ratio on the two orthogonal components.

3.3.1 Natural Period

The ambient vibration measurements were performed at the geometrical centre of plan on the roof floor of the building using a data acquisition system composed by three short period VSE-15D sensors and a SPC-35 digitizer. The sensors were oriented to the longitudinal, transverse and vertical directions. The fast Fourier transform (FFT) was applied to every record in order to calculate the spectral characteristics of displacement response. The Fourier amplitude spectrum will show a pronounced peak, centred at the fundamental mode. The empirical relationship between the natural period of fundamental mode (T) and the number storeys (N) obtained before May 11th, 2011 Lorca destructive earthquake, was T = (0.054±0.002) N (Figure 6). This result is similar to those obtained in other European cities by using ambient vibrations (e.g.: Kobayashi *et al*. 1996; Enomoto *et al*. 2000, Navarro *et al*. 2004, 2005, 2007; Gallipolli *et al*. 2010; Oliveira and Navarro 2010).

After May 11th, 2011 Lorca destructive earthquake, 34 RC buildings with different damage degree were measured in Lorca town. The results show again that the natural period of damaged buildings (T*) increases with the number of storeys (N) and EMS's damage level. The best linear fit (R^2 = 0.985, SD = 0.002) between T* and N for Lorca damaged RC buildings gives the following relationship: T* = (0.075±0.002) N (Figure 6). This increase in modal period reveals a reduction of stiffness in the damaged structures.

The relative variations of natural periods increase as the damage degree increases, as deduced when comparing the results obtained for the 23 buildings measured in Lorca before and after the earthquake. Results show that normalized period variations in both main directions are very similar, showing an average difference of about 9 %, being the longitudinal period (TL) relative increment larger than the transversal one (TT) (Figure 7).The observed trend in the average increase of T values indicates that we can expect ΔT greater than a 10% in some buildings visually classified as undamaged (14% for ΔTL and 10% for ΔTT).

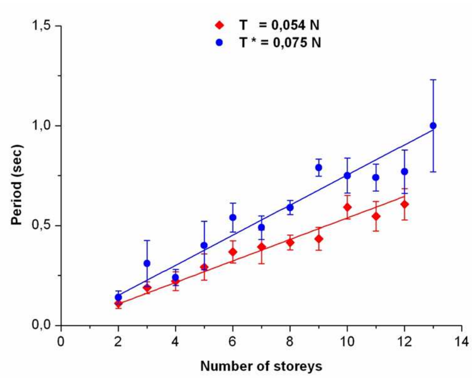

Figure 6. Relationship between the average natural period (T) and the number of storeys (N) for RC buildings of Mula and Lorca towns obtained from ambient noise analysis. Symbols and fit lines in red and blue colours correspond to buildings measured before and after the 2011 earthquake, respectively. Vertical bars represent standard deviations.

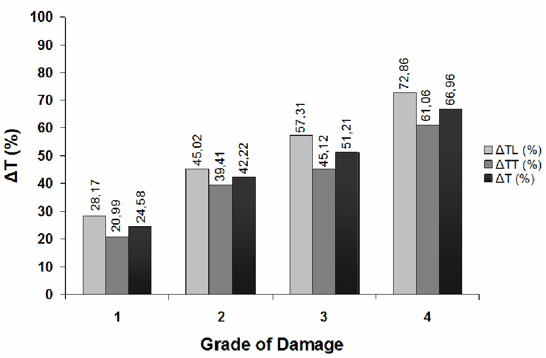

Figure 7. Means increase (in %) of natural periods (longitudinal TL, transversal TT, and average T) versus degree of damage for 23 buildings measured in Lorca town before and after the earthquake.

3.3.2 Damping factor

In order to evaluate directly the damping factor (h) of existing RC building structures in Lorca and Mula towns, Randomdec technique was applied using ambient noise measurements. This technique requires only the output of the dynamic response of a structure, and not the random excitation input. From the analysis we obtain the damped free vibration response of the structure. The results obtained from the measurements performed before 2011 Lorca earthquake in Lorca and Mula towns show h values for longitudinal and transverse components ranging from 0.9% to 15.4%, with higher values corresponding to lower buildings. The average h value for those buildings is 3.2% with standard deviation 2.6%, whereas the average damping ratio for buildings measured in Lorca town after the quake was h* is 2.2% (SD =1.6).

To find an empirical relationship between the damping factors h and h* with the number storeys N, we have assumed a typical relation $h = a\ N^b$. Damping factor data and best fits for pre- and post-earthquake cases are graphed in Figure 8.

According to previous researches (e.g. Kobayashi *et al*. 1987; Lagomarsino 1993; Dunand *et al*. 2002; Navarro and Oliveira 2005; Oliveira and Navarro 2010) the empirical relationship between the variables (h,T) has been investigated, considering the formulation (hT = constant) generally used to tackle this problem. The relationship between the damping factor h and the natural period T for swaying motion (Figure 9) has been estimated as hT = 0.75±0.04% s from data obtained before 2011 earthquake, and h*T = 0.80±0.05% s for after that.

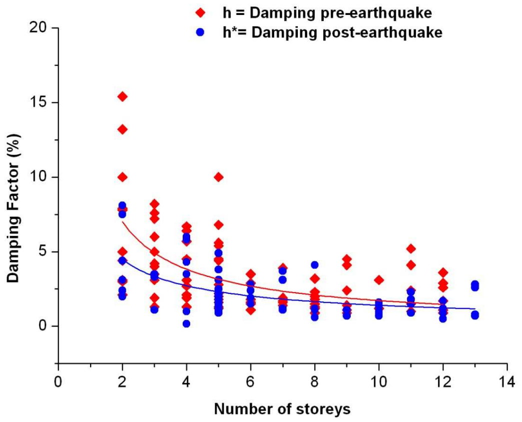

Figure 8. Relationship between the damping factor (h) and the number of floors (N) for RC buildings of Lorca town obtained from ambient noise measurements. Symbols and fit lines in red and blue correspond to buildings measured before and after the 2011earthquake, respectively.

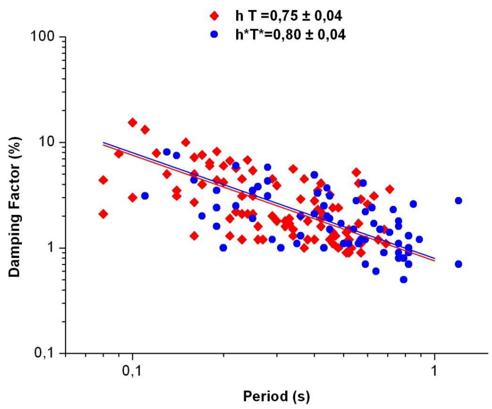

Figure 9. Relationship between damping factor (h) and natural period (T) for swaying motion of Mula and Lorca RC buildings measured before (in red) and after (in blue) the 2011 earthquake.

4. DICUSSION AND CONCLUSIONS

The geometry of geological sedimentary formations, space for sediment accommodation, and the batimetry of the bedrock in the vicinity of Lorca town are controlled by the rate of regional tectonic deformation produced by the Alhama de Murcia Fault System and other conjugated systems of faults (Egeler *et al*. 1981; Sanz de Galdeano *et al*. 1995; Alcalá *et al*. 2012).

Geological structures existing in Lorca town has been classified according to Eurocode 8 (EC8, 1998), using V_S^{30} value obtained from SPAC surveys, complemented with V_S values from shallow refraction profiles (IGME, 1992) or those deduced from N-values, and the thickness of geological formations.

The 17 geological formations identified in Lorca town (Figure 1) have been clustered into 5 main geological-seismic formations attending to their seismic behaviour, as follows: (1) The first seismic formation includes those punctual zones where conditions for EC8-D ground class have been found or could be present (Figure 4). V_S^{30} values and N-values are less than 180 m/sec and 15, respectively for those checked areas in the historic district of the town with 30-m thickness or more. This formation includes mainly geological material 1: cropland and anthropogenic fillings of variable thickness overlaying Pleistocene glacis; (2) The second seismic formation includes those zones where conditions for EC8-C ground class have been found (Figure 4). V_S^{30} values and N-values vary in the 220-380 m/sec and 5-30 range, respectively. This formation includes mainly geological materials 2 and 3: unconsolidated Holocene colluvials and alluvial terraces belonging to the Guadalentin River valley;

(3) Attending to the ranges for V_S^{30} values and N-values defined by the EC8 (1998), a large area of Lorca town can be classified as B ground-class. In Lorca town, both the geological materials 4 and 5 (i.e. the two generations of unconsolidated Pleistocene glacis and dispersed colluvials) and the geological materials 6 to 13 (i.e. the consolidated Pliocene glacis and lower-to-upper Tortonian post-orogenic medium-hard bedrock) meet the requirements to be classified into class B. An internal division has been performed in order to separate unconsolidated materials 4 and 5 from consolidated materials 6 to 13. The unconsolidated Pleistocene glacis have been classified here as the third seismic formation B2 (Figure 4), with V_S^{30} values and N-values less than 500 m/sec and 60, respectively. The consolidated Pliocene glacis and lower-to-upper Tortonian post-orogenic medium-hard bedrock have been classified here as the fourth seismic formation, B1 in Figure 4, with V_S^{30} values greater than 500 m/sec and refusal for N-values; V_S^{30} is strictly in the 660-800 m/sec range for the Tortonian medium-hard bedrocks; (4) Finally, a fifth seismic formation has been defined for those areas where conditions for EC8-A ground class have been found (Figure 4). V_S^{30} values vary from 800 to more than 1000 m/sec. This formation includes geological materials 14 to 17: Palaezoic to Triassic pre-orogenic hardest bedrock from the Alpujárride and Maláguide Complexes (Figure 1).

The ground predominant period distribution map, with values from 0.1 to 1.0 sec obtained from ambient noise HVSR method (Figure 5), reveals as a general feature an increasing in the period values from the rock outcroppings in the northern and western part of the town to the central and eastern zones, where the Quaternary materials increase in thickness. The ground predominant period range is important from an engineering perspective as it potentially affects all of the types of buildings commonly found in Lorca (buildings with between one and 12 stories).

The shift in fundamental period of damaged buildings increases as their damage degree increases. The relationship between average fundamental-mode period (T) and the number of storeys (N) here obtained for horizontal motion with measurements performed in buildings of Lorca and Mula towns before the earthquake is $T = (0.054 \pm 0.002)$ N. After the 2011 earthquake, the results obtained from 34 RC buildings with different damage degree measured in Lorca town gives the expression: $T^* = (0.075 \pm 0.002)$ N. This period elongation after the quake reveals a stiffness degradation of the structures.

In contrast to natural frequency, damping ratio does not show a significant variation with earthquake damage degree. Variations of this parameter calculated here are quite small and sometimes of the same order as the measurement errors. This result points out that damping parameter is a bad indicator of damage in structures.

The product of damping coefficient and natural period for swaying motion remain near constant when we compare hT values obtained before and after 2011 earthquake, 0.75±0.04% and 0.80±0.05%, respectively. This result suggests the most effective factor dominating hT value could be the soil condition of each site.

Although damaged buildings in Lorca town (Figure 2) are widespread in all districts of the town, with different levels and percentages, this damage distribution is specially concentrated in areas where predominant period of the ground is between 0.3 and 0.5 s. (e.g. La Viña, La Alberca, and La Alameda districts). The significant duration of the May 11th shaking has probably reduced or avoided the resonance effect. Nevertheless, the energy input spectra of ground motion - obtained convolving the transfer functions derived from SPAC 1-D models (SP in Figure 1) with the record of Lorca IGN station (Alguacil *et al.* 2012) - clearly show that most of the energy supplied by the ground is in the range of 0.3-0.6 sec. In this period range, a pseudo-velocity level of 100 cm/sec was exceeded. Considering the natural period rage of buildings, this means that seismic demand has been quite high for buildings with 4 to 6 stories. From these results, it is possible to infer the influence of site effects on the damage distribution in Lorca town. Nevertheless, particular attention should be paid to the correlation between observed spatial damage distribution and not only the resonant frequencies of the ground but also the frequency content of the earthquake.

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