16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2282 (Abstract ID)

Registration Code: S-C1460737864

AMBIENT NOISE MEASUREMENTS IN THE CITY OF LORCA (SE SPAIN) FOR SEISMIC MICROZONATION

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Abstract

A M_w 5.2 earthquake shook the city of Lorca, in Murcia region (SE-Spain) on 11 May 2011 at 18:47 local time. The main shock was preceded by a large Mw 4.5 foreshock, about two hours before. The strongest aftershock, around four hours later, reached M_w 3.9. The event caused nine fatalities and more than 300 people were injured in a town with a population of around 60000 in an area of 7 km2. Around 1000 buildings, including residential, cultural heritage, schools, government buildings, healthcare, security facilities, etc., were affected with different degrees of severity. Damage was concentrated in several areas of the town where around 40% of buildings were affected. In the historical center 16% of buildings were damaged. Historical heritage was severely affected including old churches and medieval wall towers while nearby towns and provinces were not seriously affected.

Within the two years following the earthquake in Lorca, several ambient noise measurement campaigns including both single-station and multi-station array configurations were performed in order to constrain seismic properties of the subsoil in the city and its surroundings. Single-station ambient-noise records were obtained at 86 sites in Lorca, mainly in its urban area. Additionally, at 13 sites, nine three-directional digital tromographs were deployed in 2-D array configurations, characterized by dimensions of the order of 100 m. Ambient noise measurements in the vertical component were used to retrieve the relevant effective dispersion curve of Rayleigh waves by considering ESAC and f-k approaches. At each measurement point within the array, horizontal-to-vertical spectral ratios (HVSR) were also computed. Furthermore, polarization analysis was carried out, which allowed detecting possible anisotropies in the ambient vibration wavefield.

The dispersion and HVSR curves obtained at each site were jointly inverted by considering a genetic algorithm (GA) approach, assuming that the monitored ambient vibration wavefield is dominated by surface waves including both Love and Rayleigh waves with relevant higher modes. By this procedure, S-wave velocity profiles, along with the relevant uncertainties, were estimated at each site up to depths of the order of hundreds of meters.

The obtained results, including HVSR amplitude mapping, reveal that possible ground motion amplification by local soils is not significant in most of the Lorca urban area and they also suggest the presence of significant lateral heterogeneities in the subsoil structure, resulting from past tectonic activity of major faults present in the region. The few very local resonance show~~s~~ no apparent correlation with observed damage. The lateral heterogeneities in observed damages probably rely on different vulnerability levels of buildings

Keywords: Soil characterization, Site effect, Microzonation, Lorca

1. Introduction

On 11 May 2011, a seismic sequence (17:05 M_w 4.5; 18.47 M_w 5.2; 22.37 M_w 3.9) affected Lorca, a moderate size town (population of around 60,000) located along the *Alhama de Murcia* active fault system in SE Spain. Despite the moderate magnitude of the main shock M 5.2, the event caused nine fatalities and more than 300 people were injured. It was a huge shock in the whole country since the only fatalities from earthquakes in the 20th century were in 1956 (11) and 1969 (4).

Earthquakes are not infrequent in Murcia region, where Lorca city is located. Several events in the historical record reached maximum intensity EMS-98 VIII (e.g., one in 1674 and two in the 1911 sequence), while in the last 20 years a number of events have occurred in the same region in 1999, 2002, and 2005 of magnitudes 4.8, 5.0 and 4.7, respectively. These three events reached intensities EMS98 VI-VII, causing damage and economic losses in several towns in the region.

The city suffered relevant damage reaching VII EMS98 Intensity. Only one building collapsed while about 1164 were seriously damaged including residential, cultural heritage, schools, government buildings, healthcare, security facilities, etc. Historical heritage was severely affected, including old churches and medieval wall towers. Nearby towns and provinces were not seriously affected.

Historically, the town of Lorca was damaged by the earthquakes occurring in 1579 and 1674 (VII and VIII EMS intensity, respectively). [1] and [2] found a noticeable similarity of the damages caused to the cultural heritage by the 1674 and the 2011 seismic sequence. More recently, three earthquakes shook the region of Lorca in the period 1999-2005 with magnitudes ranging between 4.7 and 5.0 (see e.g. [3]).

Fig. 1 – Typical damage. Left: collapsed building. Right: collapsed roof and cupola of the church known as *"Iglesia de Santiago"*.

The damage pattern in Lorca showed concentrations in several unevenly distributed areas in the town where around 40% of buildings were affected and which have been associated to soil local amplification effects (e.g. [4]).

[5] determine the ground fundamental periods from ambient noise HVSR method, finding periods which vary from 0.1 to 1.0 s showing an overall trend to increase in relation to the thickness of Quaternary formations and refers to the influence of unconsolidated Quaternary materials on the observed damage distribution of Lorca earthquake.

[6] use the HVSR method to analyze ambient noise at 19 sites in Lorca associating the observed low fundamental soil frequencies of around 1 Hz to the Quaternary 100-200 m thick deposits, interpreting the peaks obtained in most of the sites located on soft soil as related to soil fundamental frequency while not observing such peaks at the majority of sites located on stiff soils. They also find that their HVSR results are consistent with a generally decreasing predominant frequency from northern and western rock outcrops toward the less consolidated quaternary formations in the central and eastern zones of Lorca.

The detection of possible local resonance effects eventually responsible for ground motion amplification and enhanced damages is of great importance for city planning activities devoted to reduce future damages caused by earthquakes. The aim of this study is to analyze the possible site effects in more detail and to constrain the seismic properties of the subsoil in the town and its surroundings. Altogether 86 single-station ambient noise measurements were performed to identify possible seismic resonance phenomena by the HVSR technique. These were complemented with Vs profiles evaluated by using ambient noise measurements carried on with 2D array configurations at 13 sites.

2. Geological setting

The 2011 seismic sequence in Lorca lasted for more than two months, with about 140 aftershocks. Most authors in the literature (e.g. [7]) locate the mainshock on the *Alhama de Murcia* fault system (AMF) principally connected with the Europe-Africa motion which runs in a NNE-SSW direction along 100 km in the eastern Betic Cordillera (Fig. 2).

The AMF is at present mostly compressional with an oblique reverse motion where the hanging wall moves towards the south to southeast ([8]). The correlation between the mainshock and the causative active fault is not straightforward since the tectonic structure (AMF) is represented by a complex fault system with a branched geometry and no surface rupture was observed (see e.g. [9]).

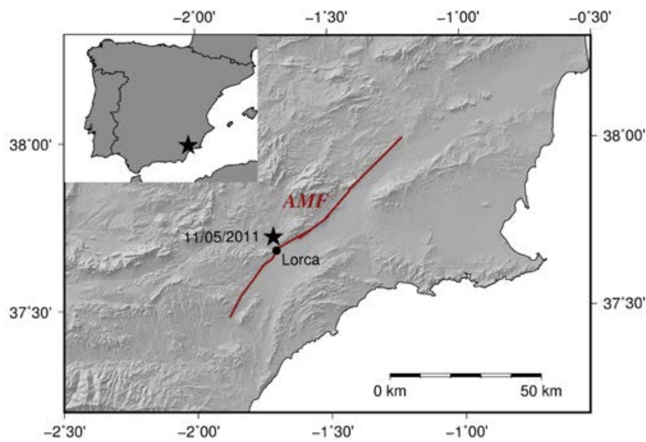

Fig. 2 – Lorca location map and AMF fault

The urban geology of Lorca town is formed by Paleozoic rock outcrops in its western part where the historical center is located on the buttresses of the castle, Miocene materials (marls and conglomerates) to the northwest and soils formed by quaternary Pleistocene soft rocks (Glacis). The most recent developments of the town in the East are situated on recent Holocene colluvial and alluvial deposits. The sediment thickness tends to increase towards the Guadalentín River Basin. Figure 3 shows an aerial view of Lorca and a geological cross section from [5] in the direction indicated in the plan view of the town.

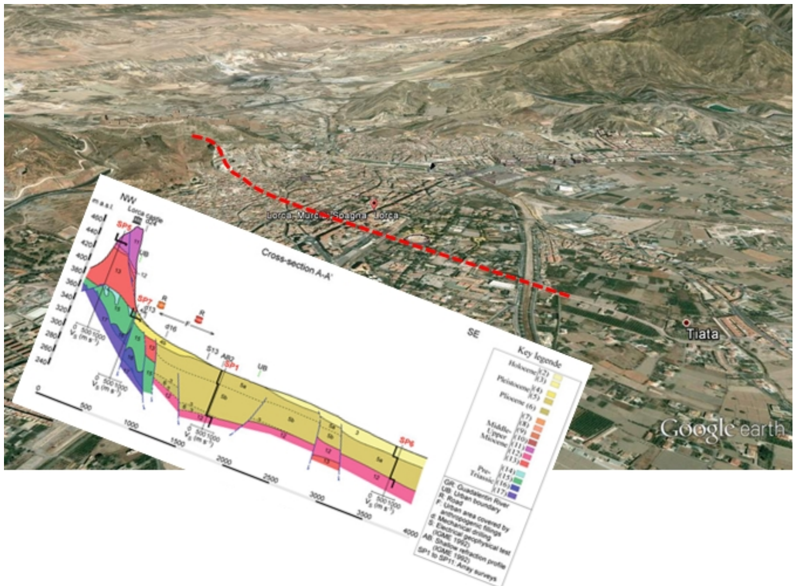

Fig. 3 – Aerial view of Lorca and geological cross section after [5].

As described above, most buildings in Lorca are located on Quaternary rocks. In general, potential energy trapping is expected at eventual impedance contrasts located at the contact between Tertiary bedrock and Quaternary rocks and/or between Holocene soils (heterogeneous formations including croplands, anthropogenic fillings, alluvial terraces, colluvial and glacis) and Pleistocene rocks.

Sharp variations are also to be expected in the thickness of Quaternary deposits (from tens to hundreds of meters) moving SE-ward, due to the presence of normal faults (trending NE-ward). Thin quaternary deposits are expected in the Lorca Basin NW-ward of the city center.

3. Single station HVSR analysis

During two field surveys (May 2011 & May-June 2012) 86 single-station ambient noise measurements were performed to identify possible seismic resonance phenomena by the HVSR.

The location of the individual measurement sites is shown in Fig. 4 (Left) together with the boundary between the outcropping Tertiary and the Quaternary deposits. Most of the measurements were carried on in the area of Quaternary deposits where most buildings are located.

Single-station measurements were carried out by using three-component Tromino© digital tromographs, specifically developed for ambient-noise surveys. Ambient noise was recorded at 128 Hz sampling rates for at least 15-20 minutes.

The HVSR analysis has followed the criteria and standard processing schemes established in the technical guidelines developed in the framework of the European project SESAME (see e.g. [10], [11]), in the same way as the procedures when performing the field measurements during the ambient-noise surveys.

Ambient noise recordings were processed using Grilla© software package, which is following SESAME standards. Recorded traces were subdivided into non-overlapping windows of 20 s length after an automatic selection based on STA/LTA ratio, which keeps only those windows with ratio below 2 in order to exclude

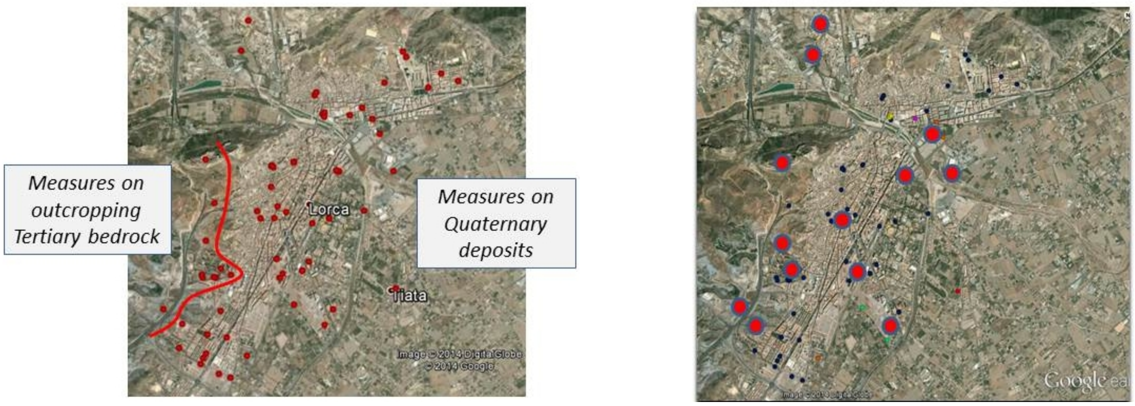

Fig. 4 – Left: Location of single-station ambient noise measurements. Right: Location of array configurations.

non-stationary transients present in the records (e.g. local traffic). Each window was base-line corrected, padded with zeros and tapered with a Bartlett window. FFT and amplitude spectrum were obtained for each window and each component, and smoothed applying a triangular window with 10% width of the central frequency. The H/V spectral ratio is computed at each frequency, for each window, using the geometric mean of the N-S and E-W components. Spectral ratios from all time windows were averaged to compute a mean HVSR curve along with the 95% confidence interval.

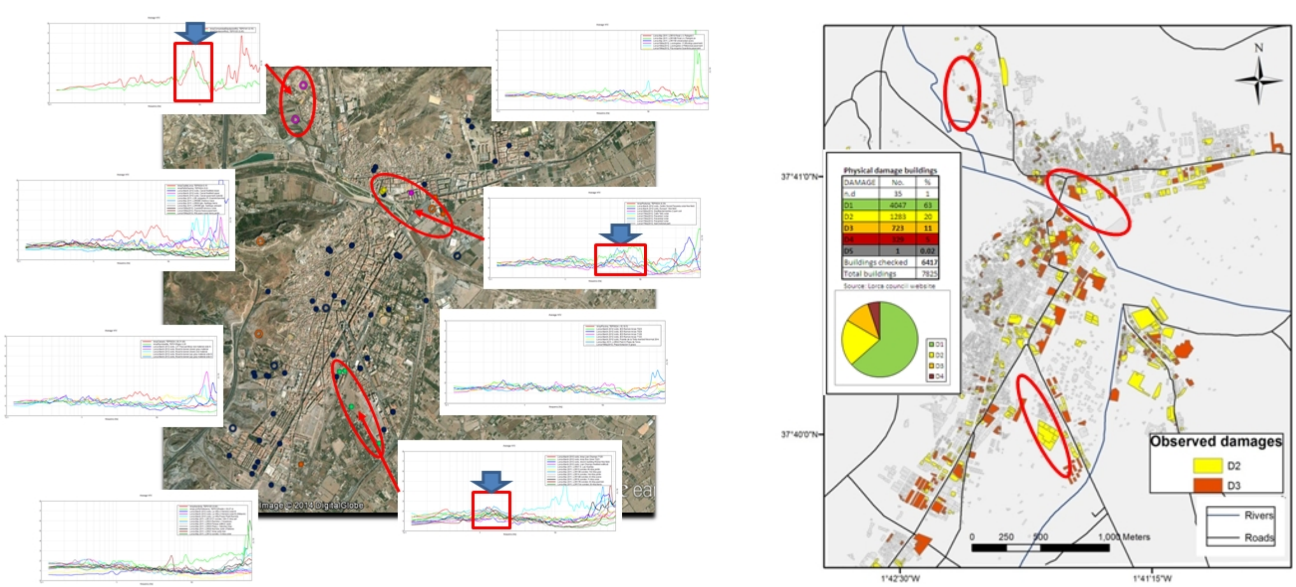

Fig. 5 – Left: Three areas where significant local resonance phenomena are observed. Right: Observed damage (only D2 and D3 from EMS98 Damage Scale) and location of the three areas in right figure.

The HVSR results show no significant resonance phenomena. Fig. 5 (Left) depicts the typical H/V ratios as a function of frequency grouped according to their location in the different parts of the city. Only at three small areas significant resonance is observed. In Fig. 5 (Right) observed damage according to the Damage Scale of EMS-98 (D0 to D5). Only most significant damage is shown (D2: moderate damage and D3: heavy damage), representing 31% of total buildings affected and 86% of buildings with significant damage. When the locations of the three areas where significant resonance phenomena are observed are overlaid on the damage map (D2 to D3 degrees) no clear correlation is apparent.

4. Shear-wave velocity profiles

To better understand the general lack of resonance, Vs profiles have been evaluated by using ambient noise measurements carried on with array configurations at 13 sites at the locations shown in Fig 4 (Right).

Array locations have been selected to sample most important Quaternary and Tertiary formations present in the area. At each site, a set of nine tromographs has been deployed along cross-shaped configuration with arms dimensions of the order of several tens of meters. Not less than 20 min ambient noise records have been analyzed by using ESAC and f-k analyses to identify Rayleigh waves effective dispersion curves.

Rayleigh Waves dispersion curves and HVSR curves are sensitive to different aspects of the Vs profile in the subsoil ([12]). This can be used to reduce the strong non-uniqueness of inversion results by jointly considering dispersion and HVSR curves for retrieving the Vs profile by inverting experimental data ([13]). Several procedures are available for this purpose and, among these, the Genetic Algorithm Technique ([14]) has been considered here.

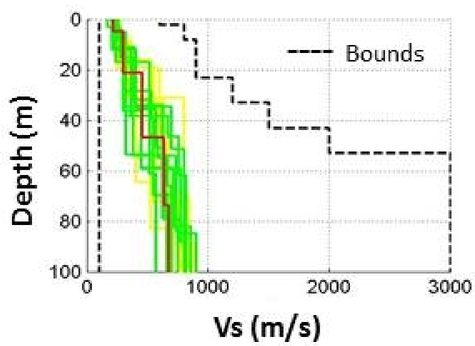

Fig. 6 – Typical shear-wave velocity profile

In general, results from the shear wave velocity profiles show that Vs values vary smoothly with depth. In Fig.6 a typical shear-wave velocity is shown. Fig. 7 depicts the shear wave velocities for the different materials in the subsurface. Quaternary shear wave velocities range from 150-500 m/s for the softer Holocene materials to 700-900 m/s of Pleistocene soft rocks. For the older formations (Miocene and Paleozoic) velocities range from 350-500 m/s to more than 1000 m /s.

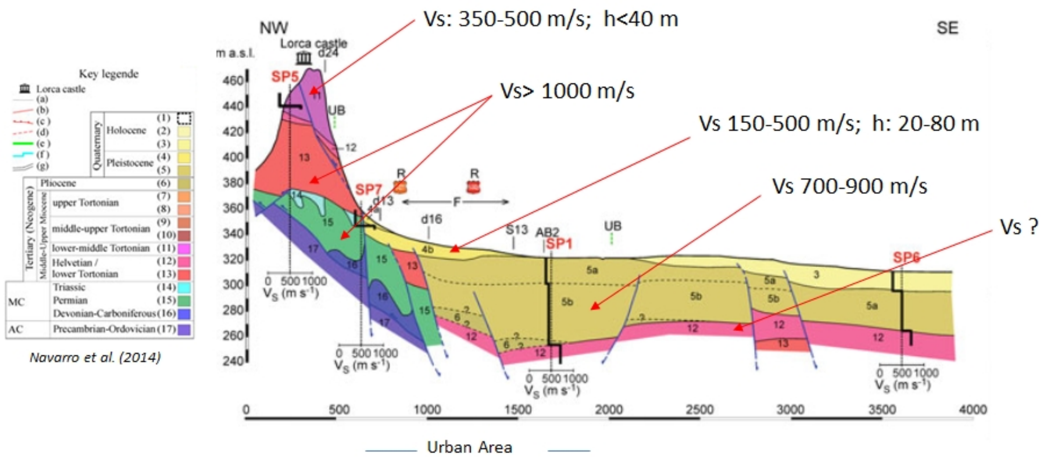

Fig. 7 – Estimated shear wave velocities for the different geological materials in the subsurface of Lorca using geological cross-section by [5].

5. Conclusions

Dense ambient noise measurements carried out in Lorca at 86 single-station sites and 13 2D array configuration sites sampling the urban area of the town where most of the building stock is located- have allowed for a more detailed characterization of possible local soil amplification effects.

Despite the moderate M_w 5.2 magnitude of the 2011 earthquake, the city of Lorca suffered relevant damage. More than 1000 buildings including residential, cultural heritage, schools, government buildings, healthcare, security facilities, etc., were severely damaged. The damage pattern in Lorca showed concentrations in several unevenly distributed areas in the town where around 40% of buildings were affected and which have been associated to soil local amplification effects.

The results of our ambient noise HVSR analysis show that, in general, no significant resonance effects (soil amplification) are observed. However, Holocene deposits are characterized by significant lateral heterogeneities which may originate those significant impedance contrasts responsible for the few resonance phenomena locally observed.

Overall, results of Vs profiles evidence a smooth variation of shear wave velocities with depth. Shear-wave velocities Vs range from 150-500 m/s for the softer Holocene materials to more than 1000 m /s for the oldest Paleozoic formations.

The damage caused in the urban area of –Lorca by the 2011 earthquake does not correlate with the few significant resonance phenomena observed very locally. Thus, lateral heterogeneities in the observed damage pattern most probably rely on different vulnerability levels of buildings.

6. Acknowledgements

Part of the work in this study was supported by the Spanish projects CGL2007-62454, and CGL2010-11831-E.

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