Introduction

The 11th May Lorca earthquake (Mw 5.1) has been the focus of seismological and fault-activity research during the last years in Spain, with official field reports of different governmental agencies (IGME, 2011; IGN, 2012). The seismic source has been clearly identified with the left-lateral strike-slip Lorca-Alhama de Murcia fault (LAF) and the seismic focus was located at depth of 2 km about 4.5 km to the north of the locality of Lorca (Fig. 1) within the upthrown block of the fault (López-Comino et al., 2012).

The earthquake was felt in the locality of Lorca with a maximum intensity of VII EMS-98 (IGN, 2012), linked to a peak ground horizontal acceleration of 0.365 g unusual for this intensity level (Benito et al., 2012). Ground shaking triggered the collapse of a multi-story building, serious damage to 899 buildings, 9 fatalities, hundred injuries and significant economic loss on the order of 450 M€ (IGN, 2012). Coseismic deformation at surface was on the order of 3-4 cm as evidenced by DinSar and GPS analyses (Frontera et al., 2012), concordant with a oblique-reverse fault rupture 4 km long and 2 km wide with 13-14 cm slip and an azimuth of 245° at 2 km depth, following the trace of the central segment (Lorca-Totana) of the LAF (Bufforn et al., 2012; Martínez Díaz et al., 2012).

In spite of the checked coseismic deformation on the upthrown block of the fault, no surface rupture was observed in the episcopal area, but numerous slope movements in a broad area of about 100 km² (Alfaró et al., 2012). The present paper reviews and analyzes the numerous set of slope movements in relation to the ESI-07 macroseismic scale (Michetti et al., 2007) and update the study previously performed by Silva et al. (2013) based on the field
analysis of the inventory of mass movements provided by Alfaro et al. (2012). The resulting distribution of ESI-07 intensity values are compared and combined with the EMS intensity values reported by the IGN (2012) in order to offer a more realistic scenario on the seismic hazard of the zone.

**Analysis of slope movements**

Slope movements triggered by the earthquake occurred in three different geomorphological contexts (Alfaro et al., 2012): Type 1) Rock falls and rock avalanches on the steep cliffs of structural reliefs. These correspond to tabular reliefs and steep cliff zones of cuesta-type reliefs carved on variably weathered Miocene marly calcarenites, but also to a minor extent on sandstones and conglomerates. Most of them occurred in the structural reliefs culminating the Late Neogene antiform of La Tercia Range north of Lorca, Peña Rubia structural relief, around the Lorca medieval Castle and in the series of cuesta-type reliefs (e.g., Cejo de Los Enamorados, Rambla 17 Arcos) flanking the Guadalentín valley upstream Lorca. This kind of slope movements are the most prominent one with individual mobilized material on the order of several cubic decametres to about 1000 m$^3$ and maximum run-outs of about 200 m (Alfaro et al., 2012). Only 31 cases reached dimensions up to 100 m$^3$, 11 of those close to 1000 m$^3$. In the rest of the cases (89) total mobilized volumes were between 10-100 m$^3$. Individual blocks can reach considerable sizes between 10-30 m$^3$. In the vicinity of the Lorca Castle, Peña Rubia and La Tercia Range, rock-falls left impact marks of metric scale on asphalt roads and non-asphalted tracks. In other affected zones (e.g., Cejo de Los Enamorados and Rambla 17 Arcos), heavily damaged tree trunks by block impacts were observed.

The more far-away case, occurred in the vicinity of the archaeological site of La Bastida (Totana) about 12.5 km NE of the epicenter (Silva et al., 2013). In this case minor rock-falls occurred, but main slope effects were linked to the remobilization of large blocks (ca. 100-200 m$^3$) resting in unstable position on the slope. Similar cases occurred during the Mw 4.8 La Paca (2005) earthquake, where locally large sized blocks (ca. 200 m$^3$) detached from steep slopes during the previous Mw 5.0 Bullas (2002) event were re-mobilized several tens of meters under VII EMS intensity values in low steep slopes (Rodríguez-Peces et al., 2011). In this case the steeper slope of La Bastida zone (> 40%) facilitated block remobilization under lower intensity values.

Type 2) Rock falls and soil slides in near-vertical slopes of canyon-like valleys, where rock and soil blocks detached from the upper half of the steep valley margins. Most of them occurred in N-S oriented deep rambla valleys and badlands areas in the central sector of the Lorca Neogene basin adjacent to La Serrata relief. These valleys are carved in relatively soft Miocene marly and silty materials north of Lorca (Bcos. Hondo, Cuesta Colorada and Badlands of El Dorado, La Serrata) generating unstable slopes where slope movements are frequent.

This category mobilized volumes between 1 and 10 m$^3$, and attains the 18% (44 cases) of the mass movements triggered by the earthquake. However in some cases these slope movements occurred assembled (Bco. Hondo; Fig. 2) mobilizing volumes of ca. 500 m$^3$. In other cases, small rambla valleys in badlands zones (Bco. El Dorado; Fig. 3) complete slope-valley sections (4x10 m) fully collapsed with estimated mobilized values around 1,500 m$^3$ (Silva et al., 2013). The widespread occurrence of this kind of rock and soil falls in the zone north of La Serrata, and oversized cases, was confusing from the first reports (Alfaro et al., 2012) since they were relatively far-away (3-4 km West) from the preliminary epicentral location. Now, after the relocation of the earthquake epicenter (López-Comino et al., 2012), it is patent that this zone is in the epicentral area of the Mw 5.1 event, but also of the preceding Mw 4.5 foreshock (Fig. 1).

Type 3) Disrupted soil slides involving low cohesive soils and deeply weathered marly slopes irrespective of their orientation or position in the slope, but mainly affecting the slope toes (Alfaro et al., 2012). This category involved the mobilization of material of the order of few cubic meters (< 3 m$^3$), but some of them in the epicentral area, especially on unstable slopes can reach 10 m$^3$. This type has 77 cases, around the 38% of the slope movements occurred in the surveyed zone, most of them (92%) in the epicentral area.

Preliminary field surveys indicated that the area affected by mass movements was of ca. 50 km$^2$ (IGME, 2011) to ca. 100 km$^2$ (Alfaro et al., 2012). The Box-counting analysis of slope movements based on the ESI-07 scale displayed in figure 4 (updated from Silva et al., 2013) indicate that the perimeter of the zone affected by slope movements was of 135 km$^2$, but with an ef-
The effective area (cells with at least 1 case) is ca. 85 km². The zone affected by the earthquake (≥ VI EMS) is subdivided in 1 km² cells (Fig. 4) illustrating the frequency, density and areal extent of slope movements occurred during the 2011 Lorca event, following the ESI-07 mapping guidelines. Counting boxes are centered in the earthquake epicentre and consider increasing areas of 10, 100 and 500 km² including 256 data-points.

This analysis shows that the 100 km² box contains 173 slope movements displaying maximum values of 9 cases/km², these last located within the 10 km² box (53 cases) around the epicentral area (Bco Hondo). The 100 km² box include the city of Lorca and records peak values of 14 cases/km² around the Lorca Castle and structural reliefs of the southern border of the Late Neogene Lorca Basin. At these locations natural slope susceptibility, topographic amplification and artificial cut-slopes multiplied the expected values (Alfaro et al., 2012). Out of the 100 km² box only 77 cases occurred displaying a mean frequency of 0.5 cases/km². The observations agree with the existing empirical relationships for affected area/magnitude in which a Mw 5.1 event correspond to an affected area of 100 km² for worldwide data sets and of about 80 km² for the Betic Cordillera (Delgado et al., 2011).

Application of the Environmental Seismic Intensity Scale ESI-07

The ESI-07 macroseismic scale represents a quantification of natural effects considered in the classical macroseismic scales (MMI, MCS, MSK), including primary (surface faulting and uplift) and secondary earthquake environmental effects (EEEs) such as ground cracks, liquefaction processes and slope movements among others (Michetti et al., 2007). The ESI-07 scale has a triple entry to establish intensities. Local intensities can be derived from the size, dimension of frequency/density of secondary EEEs. In the case of slope movements is considered the volume of mobilized material in each individual locality or case. Maximum intensities can be established from the dimensions of primary effects (surface rupture length, slip or coseismic uplift) or from the areal extent of secondary effects.

Figure 4 illustrates that the perimeter area covered by slope movements is of 135 km² indicating maximum intensity VIII (ca. 100 km²), since ESI-07 intensity VII events only cover lower areas of about 10 km² (Michetti et al., 2007). On the other hand, the overall volume of mobilized material in the 256 cases is in the range of 20,000 m³ (Silva et al., 2013), with individual cases (11) in the range of 1000 m³, which also match with ESI-07 intensity VIII. The 10 km² box in the epicentral area records the 23% of the cases (59) with a high frequency/density (9 to 14 cases/km²) of slope movements. The 100 km² box records the 70% of the cases (173).

Although there was no record of surface rupture during the event (IGME, 2011), Din-Sar and GPS analyses following the event identified relative coseismic uplift of +3-4 cm in the upthrown block of the Lorca-Ahama de Murcia Fault (Frontera et al.,...
Fig. 4.- EEE Box-counting (1 km² cells) of slope movements triggered by the Lorca 2011 earthquake. Orange cells indicate a frequency ≥ 5 cases/km². Yellow cells surround the perimeter area in which natural effects were recorded. The location of other EEE and EMS (IGN, 2012) data are also illustrated. Modified from Silva et al. (2013). (Figura en color en la web).

Conclusions

Data presented here indicate that the Lorca 2011 earthquake (Mw 5.1) reached a maximum intensity of VIII degrees following the guide-lines of the ESI-07 scale. The results refine previous estimations of intensity (IGN, 2012; Silva et al., 2013). In detail, building damage-based estimations based on the EMS-98 scale (IGN, 2012) indicated that intensity VII was only reached in the environs of Lorca City covering an area of about 5 km². However, preliminary analysis based on environmental damage (Silva et al., 2013) indicated that intensity VII covered an area of about 100-82 km², extended along the range front fault of La Terca Range and southern structural reliefs of the Late Neogene Lorca basin. Now this study identifies a macroseismic area, of about 9-10 km², around the Barranco Hondo zone underwent intensity VIII. These results don’t disagree with EMS-98 intensity data evaluated from urban zones (IGN, 2012), but complete intensity data in sparsely populated zones within the Lorca Basin. This combined ESI-07/EMS-98 analysis shows that relevant number of intensity data-points around the Lorca basin help to fill EMS-98 gaps, providing more detailed seismic scenarios for further seismic hazard analyses.

Acknowledgements

This work has been funded by the Spanish research projects CGL2012-37281-C02.01: QTEC&TETICA (USAL) and CATESI-07 (IGME). This is a contribution of the INQUA TERPRO Project 1299 and the Working Group QTEC-AEQUA. Authors are grateful to the comments of J. Delgado and an anonymous reviewer.

References