Macroseismic analysis of slope movements triggered by the 2011 Lorca Earthquake (Mw 5.1): application of the ESI-07 scale

Análisis macrosísmico de los efectos geológicos producidos por el terremoto de Lorca 2011 (5,1 Mw): aplicación de la escala ESI-07

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ABSTRACT

256 slope movements were triggered during the 2011 Lorca earthquake (Mw 5.1). They mainly are rock falls and rock avalanches with maximum volumes of 1000 m^3 for 11 cases. Box counting analysis indicate that the total area affected by slope movements is of 135 km^2, but only 85 km^2 contain recorded events. The larger slope movement occurred along the main structural reliefs, deep rambla-valleys, and badlands of the zone. Box-counting also identifies a zone of ca. 9-10 km^2 in the epicentral area (Barranco Hondo) in which about the 23% of the cases occurred. The performed analysis allows to delineate and refine the intensity zones in sparsely populated zones without EMS intensity data, identifying VIII ESI-07 intensity from secondary and primary earthquake environmental effects, no detected in previous macroseismic analyses of the zone.

Key-words: *Earthquake environmental effects, slope movements, Lorca, Betic Cordillera, SE Spain.*

RESUMEN

256 procesos de ladera ocurrieron como consecuencia del terremoto de Lorca de 2011 (5,1 Mw). La mayor parte son procesos de caídas y avalanchas de rocas con volúmenes máximos que alcanzaron los 1000 m^3 en 11 casos. El análisis "Box-counting" de estos procesos indica que el área total afectada por los mismos es de 135 km^2, pero solo 85 km^2 contienen al menos un caso. Los procesos de mayores dimensiones se registraron en los principales relieves estructurales, paredes de ramblas y zonas de badlands de la zona, pero se identifica una zona de ca. 9-10 km^2 en el área epicentral (Barranco Hondo) en la que ocurrieron el 23% de los casos. El análisis permite delinear zonas de intensidades en zonas escasamente pobladas desprovistas de datos EMS, e identifica una intensidad máxima VIII ESI-07.

Palabras clave: *Efectos ambientales de terremotos, procesos de ladera, Lorca, Cordillera Bética, SE España.*

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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 epicentral area, but numerous slope movements in a broad area of about 100 km^2 (Alfaro *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

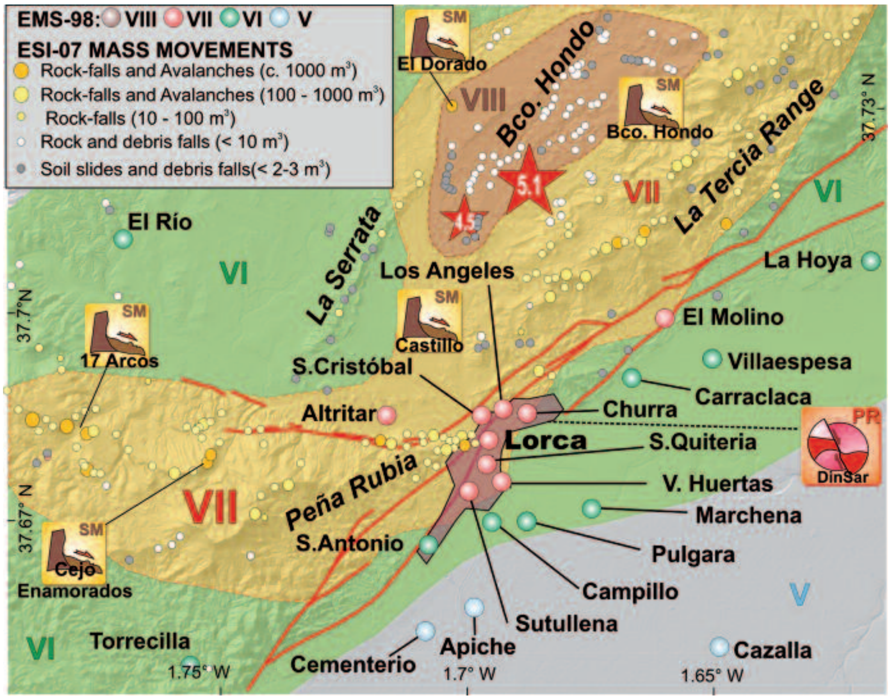

Fig. 1.- Intensity zones of the Lorca 2011 Earthquake based on ESI-07 earthquake environmental effects analyzed in this study and EMS intensity data from the IGN (2012). (Colour figure on the web).

Fig. 1- Zonas de intensidad del terremoto de Lorca de 2011 basadas en los efectos geológicos de los terremotos ESI-07 analizados en este estudio y datos EMS-98 (IGN, 2012). (Figura en color en la web).

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 geomorpholocial 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 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 Guadalentin 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 unestable 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-

Fig. 2.- Slope movements in the epicentral area. Rambla wall cracking and collapses in the Barranco Hondo.

Fig. 2.- Procesos de ladera en la zona epicentral. Agrietamientos y colapsos en Barranco Hondo.

fective area (cells with at least 1 case) of ca. 85 km^2. The zone affected by the earthquake (≥ VI EMS) is subdivided in 1 km^2 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 km^2 including 256 data-points.

This analysis shows that the 100 km^2 box contains 173 slope movements displaying maximum values of 9 cases/km^2, these last located within the 10 km^2 box (53 cases) around the epicentral area (Bco Hondo). The 100 km^2 box include the city of Lorca and records peak values of 14 cases/km^2 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 km^2 box only 77 cases occurred displaying a mean frequency of 0.5 cases/km^2. 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 km^2 for worldwide data sets and of about 80 km^2 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 km^2 indicating maximum intensity VIII (ca. 100 km^2), since ESI-07 intensity VII events only cover lower areas of about 10 km^2 (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 m^3 (Silva *et al.*, 2013), with individual cases (11) in the range of 1000 m^3, which also match with ESI-07 intensity VIII. The 10 km^2 box in the epicentral area records the 23% of the cases (59) with a high frequency/density (9 to 14 cases/km^2) of slope movements. The 100 km^2 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 coseismc uplift of + 3-4 cm in the upthrown block of the Lorca-Alhama de Murcia Fault (Frontera *et al.*,

Fig. 3.- Collapse of rambla valleys in the epicentral area (Barranco de El Dorado).

Fig. 3.- Colapso de sistemas de ramblas en la zona epicentral (Bco. de El Dorado).

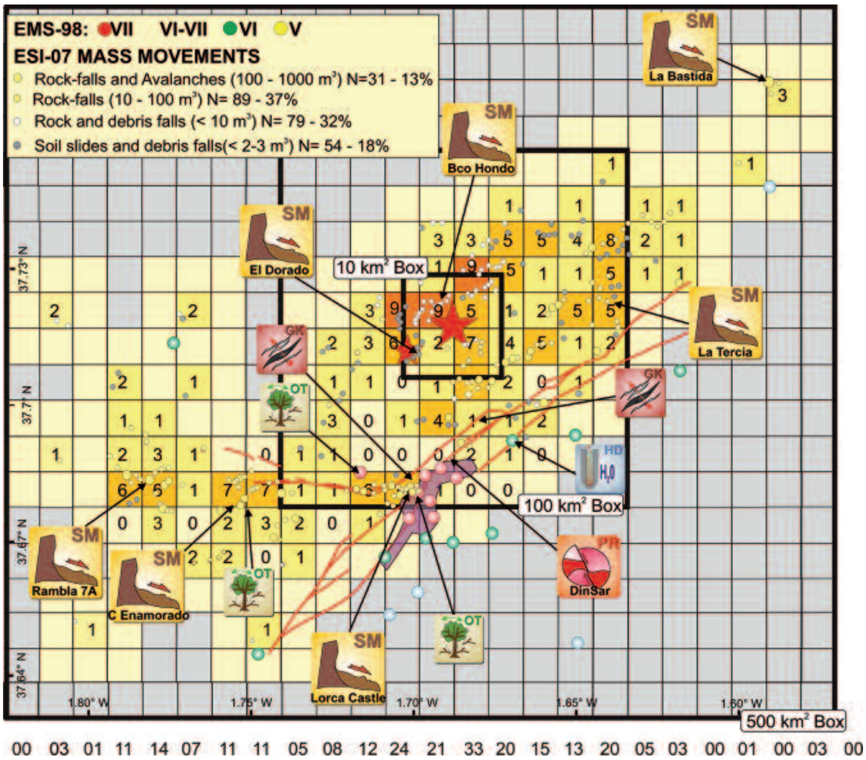

Fig. 4.- EEE Box-counting (1 km² cells) of slope movements triggered by the Lorca 2011 earthquake. Orange cells indicate a frequency ≥ 5 cases/ km². Yellow cells surround the perimeter area in which natural effects were recorded. The location of other EEE and EMS (IGN, 2012) data are also illustrated. Modified from Silva *et al.* (2013). (Colour figure on the web).

Fig. 4.- EEE Box-counting (celdas 1 km²) de los procesos de ladera generados por el terremoto de Lorca de 2011. Las celdas en naranja indican una frecuencia de ≥ 5 casos/km². Las celdas amarillas rodean el perímetro del área afectada por efectos naturales. Se muestra la localización de otros EEE, así como los datos EMS (IGN, 2012). Modificado de Silva et al. *(2013). (Figura en color en la web).*

2012). This uplift value also agrees with the minimum requirements for intensity VIII events in the ESI-07 Scale (Michetti *et al.*, 2007). In fact, the high number of recorded events, when compared with previous earthquakes in the zone (Alfaro *et al.*, 2012), are in the range of the relatively high PGA values (0.36 g) recorded in Lorca 6 km away from the epicenter (VII EMS; IGN, 2012).

Consequently, it is logical to think that in the epicentral area peak PGA values exceeded the 0.36 g recorded in Lorca, within the range (0.38 – 0.45 g) of the PGA values considered in classical macroseismic scales (e.g. MMI; Allen *et al.*, 2008). The intensity zones showed in figure 1 illustrate the extent of seismic shaking of intensity VIII, VII and VI combining ESI-07 (Silva *et al.*, 2013) and EMS-98 intensity data (IGN, 2012).

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 Tercia Range and southern structural reliefs of the Late Neogene Lorca basin. Now this study indentifies a macroseisimic 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.

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