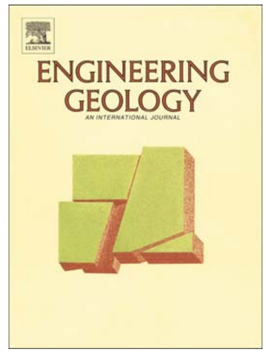
Accepted Manuscript



Seismically-Induced Landslides By A Low-Magnitude Earthquake: The M_w 4.7 Ossa De Montiel Event (Central Spain)

Delgado J., García-Tortosa F.J., Garrido J., Loffredo A., López-Casado C., Martin-Rojas I., Rodríguez-Peces. M.J.

PII: S0013-7952(15)30027-2
DOI: doi: 10.1016/j.enggeo.2015.07.016
Reference: ENGEO 4108

To appear in: *Engineering Geology*

Received date: 6 April 2015
Revised date: 8 July 2015
Accepted date: 16 July 2015

Please cite this article as: J., Delgado, F.J., García-Tortosa, J., Garrido, A., Loffredo, C., López-Casado, I., Martin-Rojas, M.J., Rodríguez-Peces., Seismically-Induced Landslides By A Low-Magnitude Earthquake: The M_w 4.7 Ossa De Montiel Event (Central Spain), *Engineering Geology* (2015), doi: 10.1016/j.enggeo.2015.07.016

SEISMICALLY-INDUCED LANDSLIDES BY A LOW-MAGNITUDE EARTHQUAKE: THE M_w 4.7 OSSA DE MONTIEL EVENT (CENTRAL SPAIN)

Delgado, J.[1*], García-Tortosa, F.J.[2], Garrido, J.[3], Loffredo, A.[1,4], López-Casado, C.[5], Martin-Rojas, I.[1], Rodríguez-Peces. M.J.[6 **]

(1) Dpto. Ciencias de la Tierra, Universidad de Alicante, Spain, Ap. Correos 99, 03080, jose.delgado@ua.es, ivan.martin@ua.es
(2) Dpto. Geología, Campus Las Lagunillas, Universidad de Jaén, 23071 Jaén, Spain, gtortosa@ujaen.es
(3) Dpto. Ingeniería Civil, Universidad de Granada, Campus Fuentenueva, 18071 Granada, Spain, jega@ugr.es
(4) Dpto. Scienze della Terra, Universitá di Roma – La Sapienza, P.le Aldo Moro 5, 00185 Roma, Italy, a.lofreddo@hotmail.it
(5) Dpto. Física Teórica y del Cosmos, Universidad de Granada, Campus Fuentenueva, 18071 Granada, Spain, clcasado@ugr.es
(6) Dpto. Geodinámica, Universidad Complutense de Madrid, Madrid, Spain, martinjr@geo.ucm.es

*Corresponding author

** Authors in alphabetical order.

Abstract: The Ossa de Montiel (2015/02/23, M_w 4.7) earthquake struck the central part of Spain and was felt far from the epicenter (>300 km). Even though ground shaking was slight (I_{max} = V, EMS-98 scale), the earthquake triggered many small rock falls, most at distances of 20-30 km from the epicenter, greater than previously recorded in S Spain (16 km) for earthquakes of similar magnitudes. The comparative analysis of available data for this event with records from other quakes of the Betic cordillera (S and SE Spain) seems to indicate a slower pattern of ground-motion attenuation in central Spain. This could explain why slope instabilities occurred at larger distances. Instability was more frequent, and occurred at larger distances, in road cuts than in natural slopes, implying that such slope types are highly susceptible to seismically induced landslides.

Keywords: Landslide, rock-fall, earthquake, peak ground acceleration, epicentral distance.

Introduction

The maximum distance at which seismically induced landslides occur is a function of the magnitude of the triggering earthquake (Keefer, 1984). Based on data from 40 worldwide earthquakes, this author proposed upper-bound curves for maximum distances at which seismically induced landslides occur, as a function of event magnitude. However, successive works have shown that in some cases, epicentral distances for some induced landslides may exceed such upper-bound curves (Rodríguez et al., 1999; Prestininzi and Romeo, 2000; Bommer and Rodríguez, 2002; Hancox et al., 2002; Keefer, 2002; Rodríguez, 2006; Delgado et al., 2011a; Wick et al., 2010; Jibson and Harp, 2012).

On February 23, 2015, an M_w 4.7 earthquake took place in central Spain (Fig. 1). This seismic event triggered numerous slope instabilities, most occurring at epicentral distances larger than those expected from upper-bound curves proposed by Keefer (1984; Fig. 1). Extensive field work was conducted immediately after the event, in order to make an inventory of the induced landslides. With the data compiled, an analysis was performed on the likely causes contributing to instabilities at such large distances.

The Ossa de Montiel earthquake

The Ossa de Montiel event took place near the southern limit of the Iberian Massif, the stable part of the Iberian Peninsula (Eurasian plate). This area is characterized by a Mesozoic cover (marls, limestone, and dolostone) and a Paleozoic basement. This region is affected by infrequent low-magnitude seismicity. In fact, according to the Spanish Seismic Catalog (IGN, 2015a), this M_w 4.7 event is the largest ever recorded (together with another that occurred in 2007). The calculated focal depth was 17 km (IGN, 2015b). The focal-mechanism solution for this event corresponds to a normal fault striking E-W (Fig. 1). Even though very slight to negligible damage was reported (I_{max} = V, EMS-98 scale), the earthquake was felt at large distances, more than 300 km away from the epicenter.

The Spanish Seismic Network has no station in the epicentral area of this event; the closest is at about 100 km from the epicenter. Figure 2 plots the peak ground horizontal acceleration (PGA), computed as the geometric average of maximum horizontal acceleration, for this event recorded by the Spanish Strong Ground Motion Network (IGN, 2015a) and the estimated PGA values for an event of the same magnitude (M_w 4.7) using the Ground Motion Prediction Equation (GMPE) in a recent re-evaluation of Seismic Hazard in Spain (Martínez Solares et al., 2013). According to the GMPE, expected PGA in the epicentral area would be 0.040 g (ranging from 0.015 to 0.120 g). For comparison purposes, Figure 2 shows PGA data of three events of similar magnitude that occurred in SE Spain (Betic Cordillera): N Mula (1999, M_w 4.7, focal depth 1 km), NE Aledo (2005, M_w 4.8, 11 km) and Lorca (2011, M_w 5.1, 4 km), with epicenters located at about 150 to 170 km from the study zone (see Figure 1 for epicentral location of these events). For these events, PGA recorded at sites with macroseismic intensity of degree V (i.e. I_{max} of Ossa de Motiel earthquake) ranged from 0.007 to 0.043 g.

It is noteworthy that acceleration data of Ossa de Montiel event are around the average plus one standard deviation of the estimated PGA curve (Fig. 2), while PGA for the above-mentioned events with similar magnitude (M_w = 4.7-4.8) is better fitted by the GMPE estimation. This seems to point out that attenuation of ground motion for Ossa de Montiel event was lower than expected. This may be due to the fact that most PGA values used to fit this GMPE came from the Betic Cordillera (S and SE Spain), which is part of the diffuse collision zone of the African and Eurasian plates (Demets et al., 1994; Nocquet, 2012). On the contrary, the Ossa de Montiel event took place within the basement of the stable Iberian Massif. The low seismic attenuation in this stable area would explain why this event was felt at very large distances from epicenter in Spain (García Mayordomo, 2015).

Field work and landslide inventory

The field work was carried out between February 27th and March 7th 2015. The relief in the epicentral area is flat or is made up of a sequence of gentle, rolling hills surrounded by flat areas. Consequently, slopes are low, typically under 15° (Fig. 1). The only natural steep slopes are located in the Ruidera zone (SW of epicenter) and along the riverbanks in the Munera – Sotuélamos zone (E of epicenter). The field inspection focused on susceptible slopes (>20-25º) in these areas. Anthropic slopes, including road and quarry cuts, which create steep slopes several meters high, were also analyzed. Areas located N of the epicenter were directly discarded for inspection as they have completely flat relief.

Landslides can be triggered by several causes, including earthquakes and rain. According to meteorological reports, a moderate rainfall episode occurred a week before the Ossa de Montiel event. As a consequence, the crux of the fieldwork was to differentiate between seismic-induced and rain-induced recent landslides. Alfaro et al. (2012) and Jibson and Harp (2012) used the criterion of assigning a seismic origin to rock falls resting on green vegetation when there was a fresh source area near the blocks. We considered landslides to be “rain-induced” when, in addition to that criterion, there was evidence of water circulation between or around the blocks (thin layer of mud/sandy deposits with crescent marks around the blocks, or remains of vegetation transported by water and deposited between the blocks) or when no impact marks were recognizable along the slope (rain had cleaned the small fragments resulting after impacts against the slope or the road located at the foot of the slope). We considered landslides to be “seismically induced” when there was no evidence of water circulation, or when impact marks on slopes/roads conserved small fragments (sand/fine gravel) that were still recognizable.

All landslides triggered by the earthquake were of small size, with volumes ranging from 2-4 m^3 down to small rock fragments (Fig. 3). These volumes are similar to those observed during previous earthquakes in SE Spain of similar magnitude (Delgado et al., 2011a; Alfaro et al., 2011). As reported by Jibson and Harp (2012), this is consistent with the fact that ground motion during events of low magnitude is characterized by waves of short duration and high frequency that usually disrupt previously jointed (or weathered) materials. In this way, all induced landslides consisted of rock/soil falls (disrupted landslides *sensu* Keefer, 1984), the most frequent type of landslide induced by low magnitude earthquakes (Keefer, 1984). Instabilities affecting natural slopes were less frequent than those affecting road and quarry cuts.

Topographic features in the epicentral area produced a highly irregular distribution of induced instabilities. They were concentrated on slopes of Munera (10-15 km from epicenter) and Ruidera (20-25 km from epicenter), the two zones with the steepest relief in the area (Fig. 1). The disrupted landslides on natural slopes were recognized at maximum epicentral distances of 24 km; this distance increases up to 30 km for instabilities affecting road and quarry cuts (Fig. 4). To estimate the area affected by slope instabilities, a polygon surrounding all the instabilities inventoried was drawn (Fig. 1). This polygon is elongated E-W, with an estimated area of ca. 800 km^2 (Fig. 4). This area is much greater than expected from previous studies for events of this magnitude (Keefer, 1984; Rodríguez et al., 1999).

Discussion

The Ossa de Montiel event induced many disrupted landslides at very large distances, greater than those expected according to its magnitude (after Keefer, 1984; Fig. 4). Delgado et al. (2011b) summarized the causes considered by different authors to explain the occurrence of disrupted landslides at large epicentral distances: i) geological context (controlling natural susceptibility of slopes), ii) antecedent rain, and iii) seismic effects (including seismic series that progressively reduce stability of slopes, becoming unstable in a given event of the seismic series, or site effects that amplify ground motion in the slope). Jibson and Harp (2012) gave a fourth explanation for an event that occurred in the East Coast of the United States: this area is a stable margin that allowed seismic waves to propagate over long distances at a low attenuation rate. According to these authors, PGA values for a given distance were higher than those observed at other sites with greater attenuation rates (i.e. West Coast USA), favoring the occurrence of instabilities at very long distances.

In the case of Ossa de Montiel event, the geological context is similar in all zones affected by landslides during this event: subhorizontal to gently dipping, jointed rock formations (marls, limestone, dolostone), locally covered by thin colluvial/alluvial deposits. When these materials were more intensely jointed (due to tectonic or anthropic activity), instabilities were more frequent. Rain had occurred before the earthquake, making many slopes even more susceptible and prone to instability processes (erosion and undercutting of some slopes was evident during the field work). In some cases, water that infiltrated slope materials might have increased pore pressure, reducing slope strength, and favoring instability occurrence. No previous seismic events were registered in the area.

As previously mentioned, no data are available on ground motion in the area where disrupted landslides took place. Consequently, it is not possible to attribute the occurrence (or not) of landslides at a given site to differences in seismic response. However, ground-motion values may be estimated indirectly, from the GMPE of PGA with distance for Spain (Martínez Solares et al., 2013), and by comparison with the PGA recorded at sites with similar macroseismic intensity during past events that occurred in SE Spain (Fig. 2). In this way, the average PGA at the epicentral area should be 0.040 g, but with a possible range of variation between 0.007 and 0.120 g.

Nevertheless, most instabilities did not take place in the epicentral area, where relief is quite flat and few susceptible slopes exist (Fig. 1), but rather in slopes located at a certain distance away (Figs. 1 and 4C): Munera ($I_{EMS\text{-}98}$ = V, Epicentral Distance = 12 km), Ruidera (IV, 23 km) and Lezuza (No Intensity assigned, 26 km). For such distances, the expected PGA from the GMPE of Martínez Solares et al. (2013) may vary between 0.003 – 0.040 g (Epicentral Distance = 12 km) and 0.002 – 0.017 g (30 km). Because ground motion of this event seems to follow the PGA plus one standard deviation of the GMPE curve (Fig. 2), the upper values of these ranges may be a reasonable estimation of PGA. This value is close to that reported by Jibson and Harp (2012) for the most distant instabilities triggered by the 2011 Mineral, Virginia, earthquake (0.021 g). From both cases, 0.02 g may be the minimum PGA necessary for disrupted landslides to occur.

The comparison of PGA during this earthquake with those observed in previous events in SE Spain (Betic Cordillera; Fig. 2) shows that PGA during the Ossa de Montiel event was greater than that observed is SE Spain for similar epicentral distances. Maximum distances of seismically induced landslides for this event are also greater than those known for events in SE Spain (Fig. 4A): maximum distances in SE Spain ranged between 15-16 km (Delgado et al., 2011a). This value is half of the maximum recorded for the Ossa de Montiel event. These data appear to indicate that earthquake ground motion in the stable basement of the Iberian Massif attenuated slowly and induced landslides at distances greater than those occurring in the tectonically active SE of Spain. This is congruent with findings of López Casado et al. (2000), who studied the attenuation of macroseismic intensity in the Iberian Peninsula and found that intensities attenuate slowly in the west and center of the Iberian Peninsula, where well-consolidated materials of the Iberian Massif exist.

Epicentral distances were also greater than the upper bound curve proposed by Keefer (1984). This agrees well with data previously presented by Jibson and Harp (2012) for the East Coast of the United States. As a result, this behavior could be generalized, i.e. that seismically-induced landslides in tectonically stable areas are expected to occur at greater distances than in active areas as a consequence of slower ground-motion attenuation. Moreover, in stable areas instabilities occurring over the upper-bound curve proposed by Keefer (1984) should also be expected.

In addition to the above factors, it was observed that the slope reaction to seismic shaking was rather different depending on its origin: natural vs. anthropic (road and quarry cuts) slopes. Figure 4C shows the number of seismically induced instabilities (or zones where several, closely spaced, instabilities took place) recognized during field inspection. In general, natural slopes performed better than anthropic ones did: instabilities in natural slopes were less frequent and occurred at lower epicentral distances. This finding may be interpreted in terms of susceptibility of slopes: artificial slopes are more susceptible to small rock/soil falls because of the way they were excavated (frequently explosive or mechanical means), giving rise to the precarious equilibrium of isolated rock blocks on slopes. Thus these blocks fall when even minor ground motion affects the slopes.

Finally, landslides induced by this earthquake are of small size, clearly smaller than those reported by Keefer (1984). Jibson and Harp (2012), when studied the landslides induced by a Mw 5.8 event 2011, also found that landslides were of small size and they occurred at distances greater than those proposed by Keefer (1984). Differences found with pioneering work of Keefer (1984) may be attributable to the different level of investigation that recent earthquakes receive when compared with historical earthquakes. Currently, field work focuses in this problem and the smallest landslide is inventoried; some time ago, this was not the case, and induced-landslides usually were not the target of field investigation, and induced-landslides of smaller size and occurring at distances greater than those reported by Keefer (1984) probably were not reported (Jibson and Harp, 2012)

Conclusions

The Ossa de Montiel, Mw 4.7, earthquake took place in the southern area of the Iberian Massif basement. Despite the low magnitude of the event, it was felt at large distances from the epicenter. The earthquake also triggered numerous small disrupted landslides (*sensu* Keefer, 1984) in both natural and anthropic (road and quarry cuts) slopes. They occurred at distances of up to 30 km from the epicenter, a very large distance, given the low magnitude of the event, i.e. approximately twice the maximum distance recorded for previous earthquakes in SE Spain. This fact, combined with the available data of seismic acceleration for this event, suggests that ground-motion attenuation in this zone is lower than in SE Spain. Comparisons of these observations with previously reported data imply that this could be a general behavior in tectonically stable areas. The inventory of instabilities triggered by this earthquake points to that anthropic slopes (road and quarry cuts) are highly susceptible to instability, as they were more frequent and occurred at larger distances than on natural slopes.

Acknowledgements

We greatly appreciate the collaboration of the Instituto Geográfico Nacional for providing seismic data used in this study. This work has been funded by Spanish Ministry of Economy and Competitiveness, research project CGL2011-30153-C02-02, and by the research groups RNM-374 (Junta de Andalucía), TECTAC (UCM-910368) and VIGROB-184 (Universidad de Alicante). Mr. Loffredo acknowledges funding of the Università di Roma – La Sapienza (post-graduate grant).

References

Alfaro, P., Delgado, J., García-Tortosa, F.J., Lenti, L., Lopez. J.A., Lopez-Casado, C., Martino, S. (2012). Widespread landslides induced by the Mw 5.1 earthquake of 11 May 2011 in Lorca, SE Spain. Engineering Geology 137-138, 40-52.

Bommer, J., Rodríguez, C.E. (2002). Earthquake-induced landslides in Central America. Engineering Geology 63, 189-220.

Delgado, J., Peláez, J.A., Tomás, R., García-Tortosa, F.J., Alfaro, P., López Casado, C. (2011a). Seismically-induced landslides in the Betic Cordillera (S Spain). Soil Dynamics and Earthquake Engineering, 31, 1203-1211.

Delgado, J., Garrido, J., López-Casado, C., Martino, S., Peláez, J.A (2011b). On far field occurrence of seismically induced landslides. Engineering Geology 123, 204-213.

Demets, C., Gordon, R.G., Argus, D.F., Stein, S. (1994). Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. Geophysical Research Letters 21, 2191-2194.

García Mayordomo, J. (2015). ¿En qué se parece los terremotos de Lorca de 2011 y el reciente de Ossa de Montiel? In: IGME (ed.): Terremoto de Ossa de Montiel (Albacete) de magnitud 5.2. http://info.igme.es/eventos/.

IGN (2015a). Servicio de información sísmica. http://www.ign.es/ign/layout/sismo.do. (Last accessed 20/03/2015).

IGN (2015b). Tensor momento sísmico. http://www.ign.es/ign/layoutIn/sismoPrincipalTensorUltimo.do?evid=1318537. (last accessed 20/03/2015).

Jibson, R.W., Harp, E.L. (2012). Extraordinary distance limits of landslides triggered by the 2011 Mineral, Virginia, earthquake. Bulletin of the Seismological Society of America 102, 2368-2377, doi: 10.1785/0120120055.

Hancox, G.T., Perrin, N.D., Dellow, G.D. (2002). Recent studies of historical earthquake-induced landsliding, ground damage, and MM intensity in New Zealand. Bulletin of the New Zealand Society for Earthquake Engineering 35, 59-95.

Keefer, D.K. (1984). Landslides caused by earthquakes. Geological Society of America Bulletin 95, 406-421.

Keefer, D.K. (2002). Investigating landslides caused by earthquakes – A historical review. Surveys in Geophysics 23, 473-510.

López-Casado, C., Molina-Palacios, S., Delgado, J., Peláez, J.A. (2000). Attenuation of intensity with epicentral distance in the Iberian Peninsula. Bull. Seism. Soc. Am. 90 (1), 34-47.

Martínez Solares, J.M., Cabañas, L., Benito, B., Ricas, A., Gaspar, J.M., Ruíz, S., Rodríguez, O. (2013). Actualización de mapas de peligrosidad sísmica de España 2012. Gobierno de España, Ministerio de Fomento, Madrid, 267 p.

Nocquet, J.M. (2012). Present-day kinematics of the Mediterranean: a comprehensive overview of GPS results. Tectonophysics 579, 220-242.

Prestininzi, A., Romeo, R. (2000). Earthquake-induced ground failures in Italy. Engineering Geology 58, 387-397.

Rodríguez, C.E. (2006). Earthquake-induced landslides in Colombia, ECI Conference on Geohazards, Lillehammer, Paper 38.

Rodríguez, C.E., Bommer, J.J., Chandler, R.J. (1999). Earthquake-induced landslides: 1980-1997. Soil Dynamics and Earthquake Engineering 18, 325-346.

Wick, E., Baumann, V., Jaboyedoff, M. (2010). Repport on the impact of the 27 February 2010 earthquake (Chile, Mw 8.8) on rockfalls in the Las Cuevas valley, Argentina. Natural Hazards and Earth System Sciences 10, 1989-1993, doi:10.5194/nhess-10-1989-2010.

Figure caption

Figure 1. Location map of the study zone, showing the location of slope instabilities. Values in parentheses represent the assigned macroseismic intensity (EMS-98 scale). The circle reflects the maximum epicentral distance of expected seismically induced landslide occurrence according to Keefer (1984) upper bounds. Dash line is the polygon that encloses all induced landslides recognized in this study. Red star shows location of Ossa de Montiel (M_w 4.7) earthquake epicenter. Focal mechanism solution from IGN (2015b). Inset legend: (1) Iberian Massif; (2) Betic Cordillera; (3) Other Alpine domains and Cenozoic basins; (4) Epicenter of N Mula event (1999, Mw 4.7); (5) Epicenter of NE Aledo event (2005, Mw 4.8); Epicenter of Lorca event (2011, Mw 5.1).

Figure 2. Peak Ground Horizontal Acceleration (PGA) recorded during the Ossa de Montiel (M_w 4.7) and during three events of similar magnitude occurred in SE Spain. In the case of Ossa de Montiel data, PGA for site at 103 km from the epicenter was obtained by differentiation of a seismogram recorded with a broadband sensor of the Spanish Seismic Network (station ETOB). A comparison with estimated PGA from the GMPE for Spain (Martínez Solares et al., 2013) and macroseismic intensity values during past events in SE Spain is also shown.

Figure 3. Examples of disrupted landslides induced by the earthquake. A) Rock fragment resting on green vegetation. B) Rock falls of reduced volume on a natural slope. Recognizable is the source area, an impact, and a small block resting at the foot of the slope (see arrows). C) Small soil/rock failures along a road cut. D) Larger rock fall induced by the earthquake. Rock blocks were fractured during downslope movement into several blocks of smaller volume. Several blocks rest on the vegetation and others impacted on the slope and the asphalt of the road located just below the slope (see white arrows and inset).

Figure 4. (A) Maximum epicentral distance for disrupted landslides induced by the Ossa de Montiel event compared with maximum distance curve proposed by Keefer (1984). Figure also includes data of other earthquakes that induced landslides at distances greater than Keefer's curve (data after Delgado et al., 2011b, and Jibson and Harp, 2012, for the period 1980 to present). (B) Area affected by disrupted landslides during the Ossa de Montiel earthquake compared with previous maximum area curves proposed by Keefer (1984) and Rodríguez et al. (1999). (C) Distribution of instabilities regarding the nature of the slope (natural vs. anthropic) and epicentral distance.

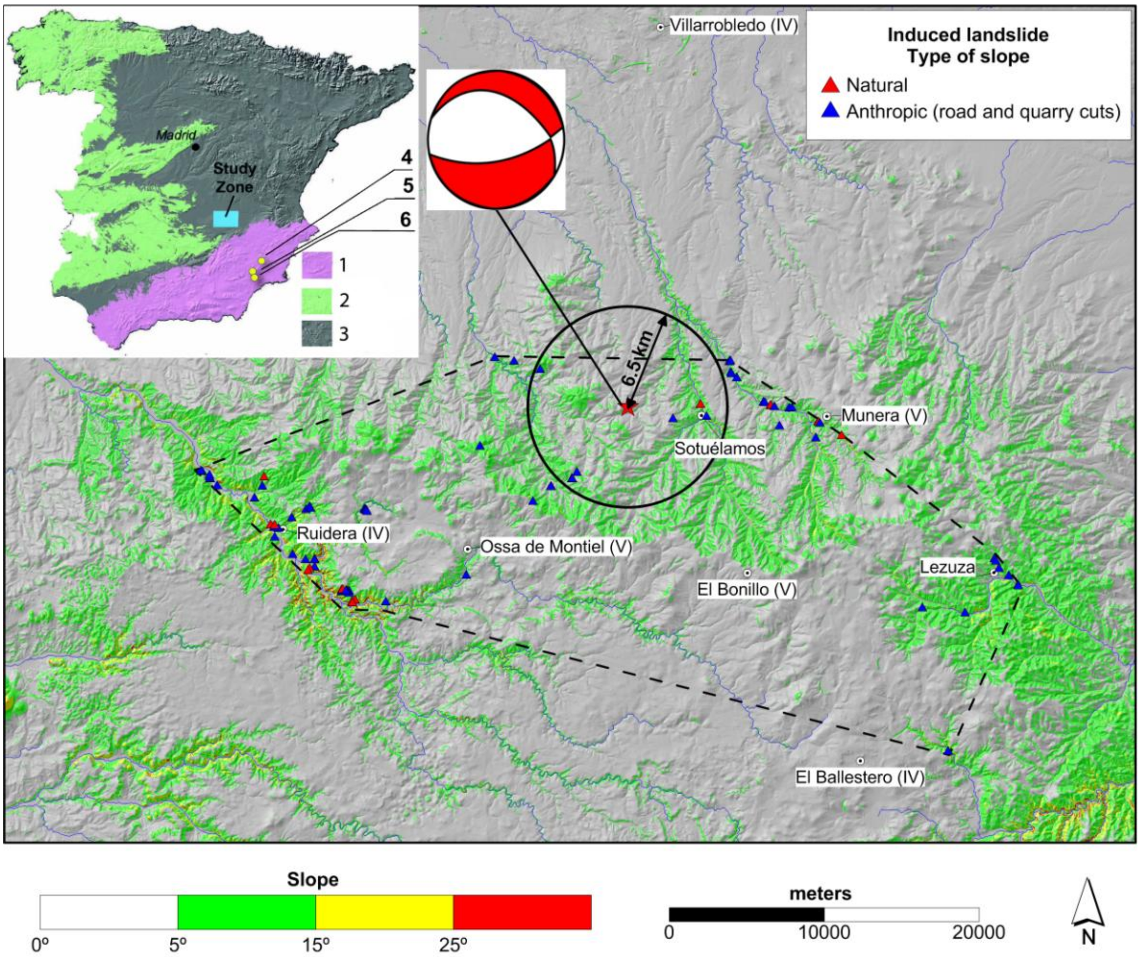
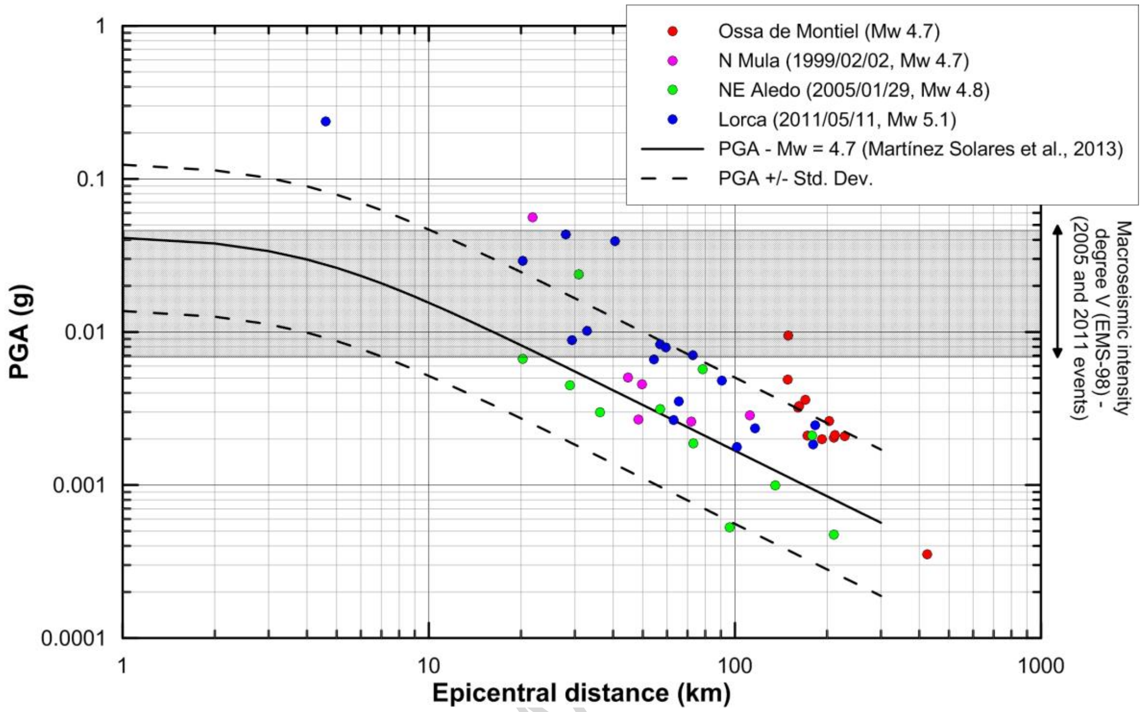

Villarrobledo (IV)
Induced landslide
Type of slope
Natural
Anthropic (road and quarry cuts)
Madrid
Study Zone
4
5
6
1
2
3
6.5 km
Munera (V)
Sotuélamos
Ruidera (IV)
Ossa de Montiel (V)
El Bonillo (V)
Lezuza
El Ballestero (IV)
Slope
0º
5º
15º
25º
meters
0
10000
20000
N

Figure 1



Ossa de Montiel (Mw 4.7)
N Mula (1999/02/02, Mw 4.7)
NE Aledo (2005/01/29, Mw 4.8)
Lorca (2011/05/11, Mw 5.1)
PGA - Mw = 4.7 (Martínez Solares et al., 2013)
PGA +/- Std. Dev.
Macroseismic intensity degree V (EMS-98) - (2005 and 2011 events)
PGA (g)
1
0.1
0.01
0.001
0.0001
1
10
100
1000
Epicentral distance (km)

Figure 2

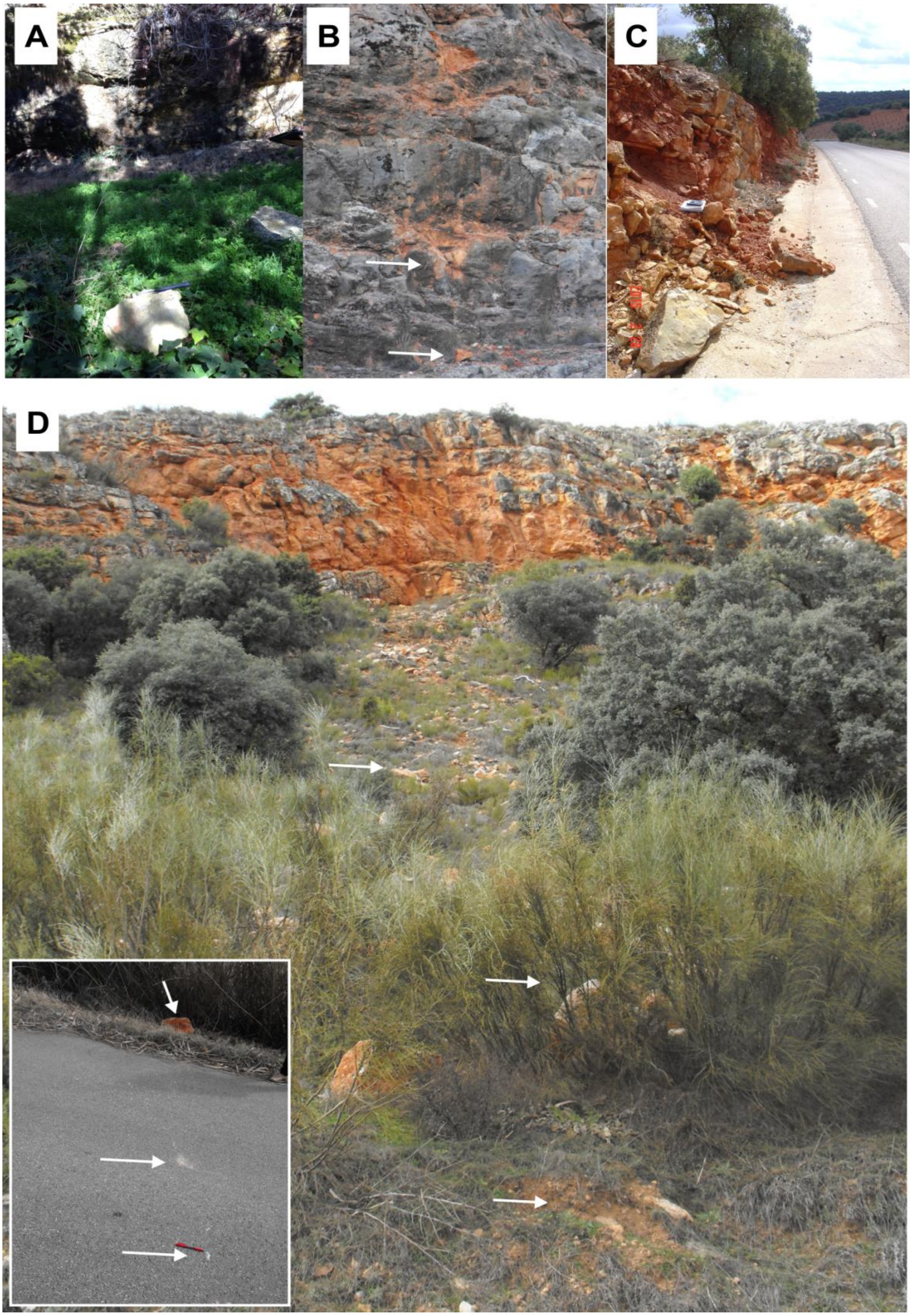
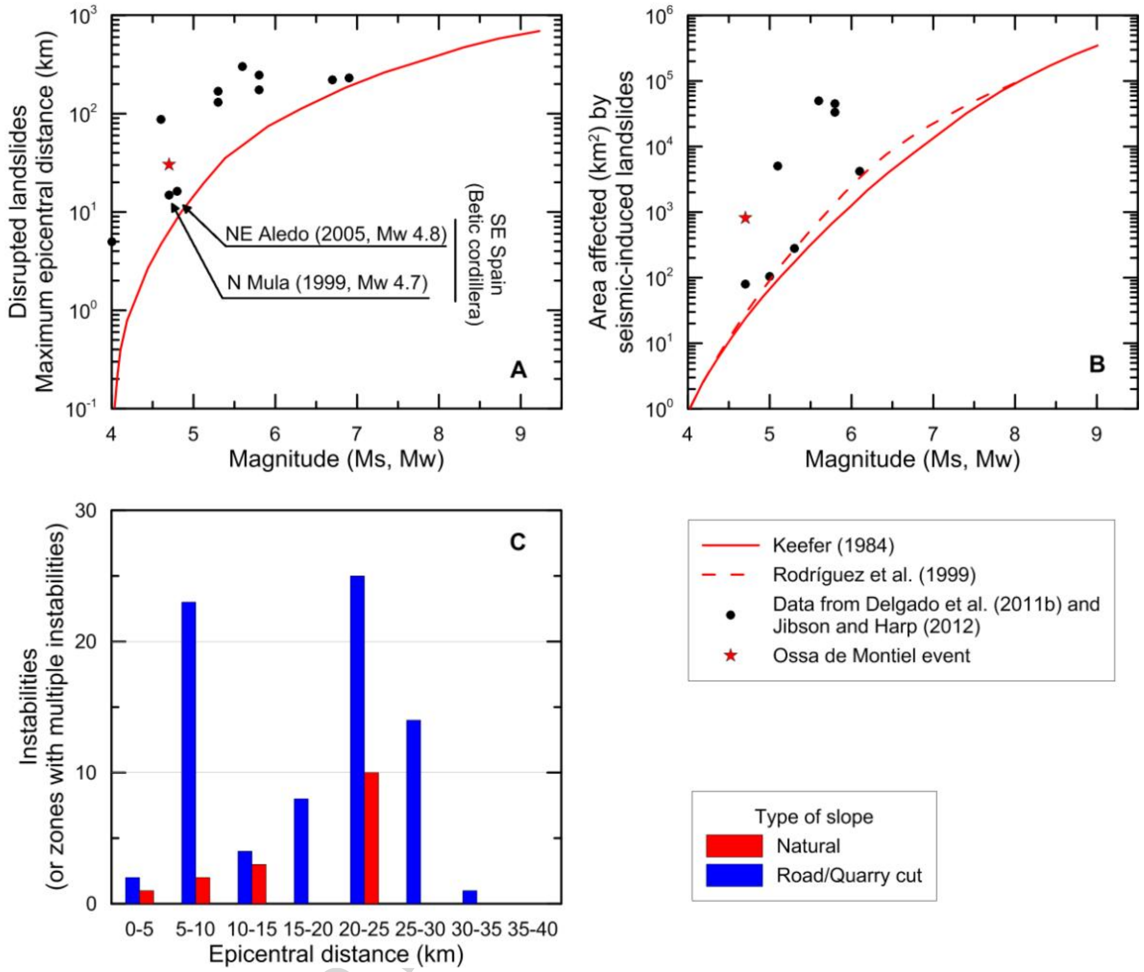


Figure 3



Disrupted landslides
Maximum epicentral distance (km)
NE Aledo (2005, Mw 4.8)
N Mula (1999, Mw 4.7)
SE Spain
(Betic cordillera)
A
Magnitude (Ms, Mw)
Area affected (km²) by
seismic-induced landslides
B
Magnitude (Ms, Mw)
Instabilities
(or zones with multiple instabilities)
C
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
Epicentral distance (km)
Keefer (1984)
Rodríguez et al. (1999)
Data from Delgado et al. (2011b) and
Jibson and Harp (2012)
Ossa de Montiel event
Type of slope
Natural
Road/Quarry cut

Figure 4

Highlights

- A low magnitude earthquake induced rock falls at large distances from epicenter.
- Maximum distances are greater than predicted by models according to event magnitude.
- Ground motion attenuated slower than in areas tectonically active of SE Spain.
- Instabilities were more frequent, and occurred at larger distances, in road cuts.