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Seismically-induced landslides in the Betic Cordillera (S Spain)

J. Delgado [a,*], J.A. Peláez [b], R. Tomás [a], F.J. García-Tortosa [c], P. Alfaro [d], C. López Casado [e]

[a] Dpt. Ingeniería de la Construcción, OO.PP. e I.U, Escuela Politécnica Superior, Universidad de Alicante, 03080 Alicante, Spain
[b] Dpt. Física, Campus Las Lagunillas s/n, Universidad de Jaén, 23071 Jaén, Spain
[c] Dpt. Geología, Campus Las Lagunillas s/n, Universidad de Jaén, 23071 Jaén, Spain
[d] Dpt. Ciencias de la Tierra y M.A. Facultad de Ciencias, Universidad de Alicante, 03080 Alicante, Spain
[e] Dpt. Física Teórica y del Cosmos, Facultad de Ciencias, Universidad de Granada, Av. Severo Ochoa s/n, 18071 Granada, Spain

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ABSTRACT

A database of seismically-induced landslides in the Betic Cordillera is presented. Data included were classified according to landslide typology. Most of them ($\approx$80%) correspond to small size, disrupted landslides (including rock/earth falls and earth slides that disorganize as mass-movement progresses) and the remaining consist mainly of coherent landslides (slumps in soils and rock-slides). Deep seated induced landslides are uncommon in the study zone and have occurred only after the few events of large magnitude reported in the Cordillera. Data available show that events of small magnitude ($M_w < 5.0$) can induce instabilities in the study zone for comparatively large distances (>10 km) when compared with available upper bound curves for maximum epicentral distances for seismic induced landslides, that concentrate along areas prone to landsliding, like river banks or slopes on soft materials, which points out the importance of the role of slope susceptibility on the occurrence of instabilities during earthquakes. Landslides in the database are then analyzed and a power-law relationship that relates earthquake size, measured as epicentral intensity (I_o), to maximum distance of induced landslide valid for the study zone is proposed. Although included data represent a clear partial and incomplete dataset, they show the landslide state of knowledge for this region.

1. Introduction

A great effort has been made in the last two decades to study and understand the problem of landslides induced by earthquakes. Because this indirect effect of shaking can be widespread, its effect may cause a major disruption in society, causing significant economic losses and deaths. This was the case for the events of Alcoy (1620) or Arenas del Rey (1884) in South Spain, where several counties and towns were severely damaged by seismic induced landslides.

Several techniques are in use to address this topic and support planning decisions towards earthquake-triggered landslide risk management (*e.g.*, [1–5]). Each one has its own requirements and implies the use of different kinds of data. Choosing among them is frequently a question of scale and availability of data: the more rigorous ones are employed for site specific studies, where detailed information about subsoil materials and properties are available, while the more generic ones are more appropriate for regional studies, where detailed data are rarely accessible.

Although seismically-induced landslides have been known for a long time in the Betic Cordillera, S Spain, there are still few studies about this topic and they have been focused on studying limited areas within the cordillera (*e.g.*, [6–13]) or describing single landslide topics [14]. No attempt has been made to develop a database for such landslides or to determine relationships between landslide occurrence and shaking parameters of events.

In this paper we present for the first time a regional database compiled for landslides induced by earthquakes occurred in the Betic Cordillera (Fig. 1). Although this database is incomplete, it represents a step forward for the progress in the knowledge of this phenomenon in the area. This database comprises landslides induced by two types of earthquakes: historical earthquakes, most of them moderate to strong events (6.0–7.0 M_w), and recent events (1945 to present) of low magnitude (≤ 5.0 M_w).

2. Seismotectonic framework

Seismicity in the Betic Cordillera is conditioned by the contact between the Eurasian and the African plates. NUVEL-1 model [15] reveals a NW-SE to NNW-SSE convergence rate of 4–6 mm/year between Southern Spain and Africa. In this geodynamic setting, NW-SE to NNW-SSE compression is combined with NE-SW extension [16].

In general, the Betic Cordillera is characterized by a continuous scattered low to moderate seismicity ($M < 5.5$; Fig. 1) inducing a low to moderate seismic hazard [17,18]. In any case, some destructive

* Corresponding author. Tel.: +34 965 903 400x2122; fax: +34 965 909 862.
E-mail addresses: Jose.delgado@ua.es (J. Delgado), japelaez@ujaen.es (J.A. Peláez), Roberto.tomas@ua.es (R. Tomás), gtortosa@ujaen.es (F.J. García-Tortosa), Pedro.alfaro@ua.es (P. Alfaro), clcasado@ugr.es (C. López Casado).

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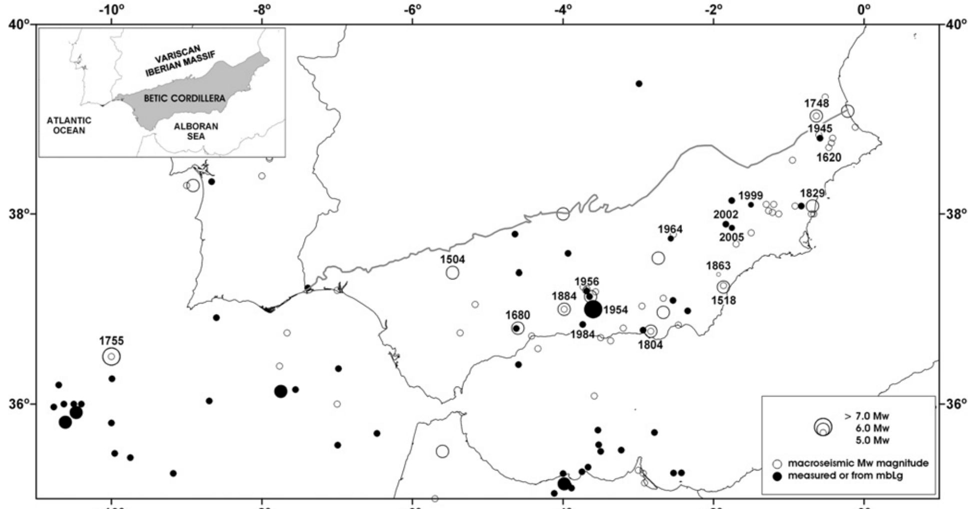

Fig. 1. Location of the study zone. Seismicity of the Betic Cordillera and nearby area for magnitudes $M_w \geq 5.0$. Earthquakes listed in Table 1 are also showed and labeled.

events in the historical period can be observed (intensities IX and IX–X) separated by long time intervals.

In most cases there is not a clear link between main epicenters and main faults observed at surface, although there is a certain correlation between some significant earthquake groupings and the main fault systems. They have preferential strikes N70–90°E, NW-SE and NE-SW [19].

Seismicity ranges from very shallow to intermediate events (50–150 km) in the region that embraces from westernmost Alboran Sea, to eastern Málaga and southwestern Granada [20,21], with a N-S trend. Some very deep events were located beneath Dúrcal (Granada) in March 29th, 1954 [22], January 30th, 1973, March 8th, 1990 [23], and lately, in April 11th, 2010, although there is no relationship among these earthquakes and the overall seismicity in this region. The 1954 Dúrcal earthquake (mb 7.1) was the biggest earthquake ever recorded in Spain, although given its depth, it was felt only with intensity V. Although intermediate and deep events are important for understanding the present tectonics of this region, revealing anomalous structures of great depth, they have little importance from a seismic hazard point of view [17].

The main source including seismicity of this area is the IGN seismic catalog [24,25], updated periodically in online digital format (http://www.ign.es/ign/es/IGN/SisCatalogo.jsp). It includes pre-1900 moment magnitude reappraisals computed using the Bakun and Wentworth approach [26,27], and recent real-time moment tensor determinations [28]. For those earthquakes included in this work without computed moment magnitude we have used the following relationship [29]:

$$M_w = 0.575 I_{max} + 1.150 \pm 0.56 \quad (1)$$

and the relationship between mbLg and moment magnitude [30]

$$M_w = 0.311 + 0.637\,\text{mbLg} + 0.061(\text{mbLg})^2 (1.7 < \text{mbLg} < 5.7) \quad (2)$$

both established specifically for Spain. Errors in location, magnitude or maximum intensity are strongly dependent of the period and available data. Table 1 resumes data for those events that induced landslides and are included in the compiled database.

3. Landslide database

The database has been compiled from a detailed review of documentation that includes newspapers, contemporary manuscripts, technical reports prepared after earthquake occurrences, Ph.D. theses, research papers and in situ inventories made by field inspection (only for events ID14–ID17) and making use of remote sensed images of the affected zones. In other cases, contacting people that felt the earthquakes was very helpful for locating some instability (only for events ID13–ID17). The final database includes 95 records of landslides induced (triggered or reactivated) by 17 earthquakes, 23 of them correspond to multiple landslides.

Maps showing the instabilities associated with these events, classified by their typology and period of occurrence (historical and instrumental events), are shown in Fig. 2. This division (historical versus recent) takes into account the fact that location of the epicenters for the historical events is based on macroseismic data, i.e., isoseismal maps or direct intensity data, using the Bakun and Wentworth [26,27] approach, while location/magnitude for the instrumental events is rather precise. Parameters derived from this second group, such as distance "epicenter to landslide", are usually more accurate than that calculated for the first group of earthquakes. The first instrumental event corresponds to the January 7th, 1945 Onteniente (M_w 4.8) earthquake (ID11).

Locating landslides induced by historic earthquakes has some limitations. Historical descriptions of the effects of shaking usually focus on casualties or on damage to structures, and little attention is paid to seismogeological effects (i.e. soil liquefaction or landslides). As a consequence, there are several documents that clearly mention the occurrence of earthquake-triggered landslides, but nothing is said about their precise location. This is the case for the September 22th, 1522 Baza, October 3th, 1713 Lorca, or December 20th, 1818 NE Lorca earthquakes [12,33,34]. Additionally, most available historical documents focus in urban areas affected by high damages, while areas of low damage are poorly described. Consequently, for historical events, landslides identified concentrate around earthquake epicenter at short distances. When location of a landslide is clearly documented, this is due to the relevance of the damages caused or to the size of landslide (*e.g.*, huge size or high concentration of instabilities affecting an area). Sometimes, descriptions refer to a geographic area, which is described to be affected by a given landslide typology. When visited, effectively, there is evidence of this type of landslide affecting such zones, but several instabilities can be recognized, some being ancient features and others being of recent occurrence, even currently active. Dating these instabilities

Table 1
Characteristics of earthquakes included in the Betic Cordillera database.

ID	Location	Date	Magnitude		Depth (km)	Location error H/Z (km)	Focal mechanism[l]	Intensity (EMS-98)		Affected area (km^2)	Maximum epicentral distance (km)			Source (Appendix A)
			M_D, m_{bLg}	M_W				Maximum macroseismic	Range for landsliding occurrence		Disrupted	Coherent	Flow/lat. spread	
1	Carmona 37.383°N, 5.467°W[a]	05/04/1504	–	6.9[c]	–	20–50[h]/–		VIII–IX	VIII–IX	–	–	17.6	–	[A1]
2	Vera 37.233°N, 1.867W[a]	09/11/1518	–	6.1[d]	–	10–20[h]/–		VIII–IX	VIII–IX	–	1.4	–	–	[A2]
3	Alcoy 38.700°N, 0.467°W[a]	02/12/1620	–	5.5[d]	–	20–50[h]/–		VII–VIII	VII–VIII	3.6	0.3	1.3	–	[A3] [A4]
4	NW Málaga 36.800°N, 4.600W[a]	09/10/1680	–	6.8[c]	–	10–20[h]/–		VIII–IX	VIII–IX	–	–	23.2	–	[A5]
5	Estubeny 39.033°N, 0.633°W[a]	23/03/1748	–	6.2[c]	–	10–20[h]/–		IX	VIII–IX	–	11.3	–	–	[A6]
6	SW Cabo San Vicente (Lisbon earthquake) 36.500°N, 10.000°W[a]	01/11/1755	–	8.7[c]	–	> 50[h]/–		X	V–VII	–	769	577	–	[A7]
7	Dalías 36.767°N, 2.833°W[a]	25/08/1804	–	6.4[c]	–	10–20[h]/–		VIII–IX	VII	857	32.5	26	–	[A5]
8	Torrevieja 38.083°N, 0.683°W[a]	21/03/1829	–	6.6[c]	–	10–20[h]/–		IX–X	VII	–	38.7	–	–	[A8] [A9]
9	Huércal–Overa 37.367°N, 1.933°W[a]	10/06/1863	–	4.2[e]	–	10–20[h]/–		VI–VII	VI–VII	66	8.5	–	–	[A5] [A10] [A11] [A12]
10	Arenas del Rey 37.000°N, 3.983°W[a]	25/12/1884	–	6.5[c]	–	< 10[h]/–		IX–X	VI–IX	3171	35.8	45.4	39.4	[A2] [A5] [A13] [A14] [A15] [A16] [A17]
11	Onteniente 38.800°N, 0.583°W[b]	01/07/1945	4.8	4.8[f]	–	10–60[i]/–		VII	V	–	15.4	–	–	[A3]
12	NW Purchil 37.192°N, 3.683°W[b]	19/04/1956	5.0	5.0[f]	5	4[j]/4[j]		VIII	VIII	–	4.8	–	–	[A18]
13	SW Galera 37.737°N, 2.567°W[b]	09/06/1964	4.8	4.8[f]	5	10[j]/20[j]		VIII	V–VIII	34	8.4	2.3	–	[A5] [A19] [A20][m]
14	W Lentegí 36.838°N, 3.738°W[b]	24/06/1984	5.0	5.0[f]	5	1–10[k]/–	Normal	V	V	104	10.4	13.6	–	[A5] [A21] [A22][m,n]
15	N Mula 38.096°N, 1.501°W[b]	02/02/1999	4.7	4.7[f]	1.1	2.2[j]/2.9[j]	Strike slip	VI	VI	80	14.8	8.8	–	[A23][m,n]
16	SW Bullas 37.883°N, 1.830°W[b]	06/08/2002	4.8	5.0[g]	1.2	2.6[j]/3.0 [j]	Strike slip	V	V	3.5	4.2	–	–	[m,n]
17	La Paca 37.854°N, 1.756°W[b]	29/01/2005	4.7	4.8[g]	10.9	2.1[j]/0.2[j]	Strike slip	VI	V–VI	18	16.3	–	–	[m,n]

[a] Macroseismic location [25].
[b] Instrumental location ([24], updated to 2009).
[c] Using the Bakun and Wentworth approach [26,27,31].
[d] From maximum intensity [29].
[e] Using the Bakun and Wentworth approach [25,26,27].
[f] From mbLg [30].
[g] Instrumental ([24], updated to 2009).
[h] Estimated error [25].
[i] Usually, estimated error for earthquakes in the period 1920–1980 [32].
[j] Computed error ([24], updated to 2009).
[k] Usually, estimated error for earthquakes since 1980 [32].
[l] After Stich et al. [52].
[m] Data from interviews to people that lived the earthquake.
[n] In situ investigation after the earthquake.

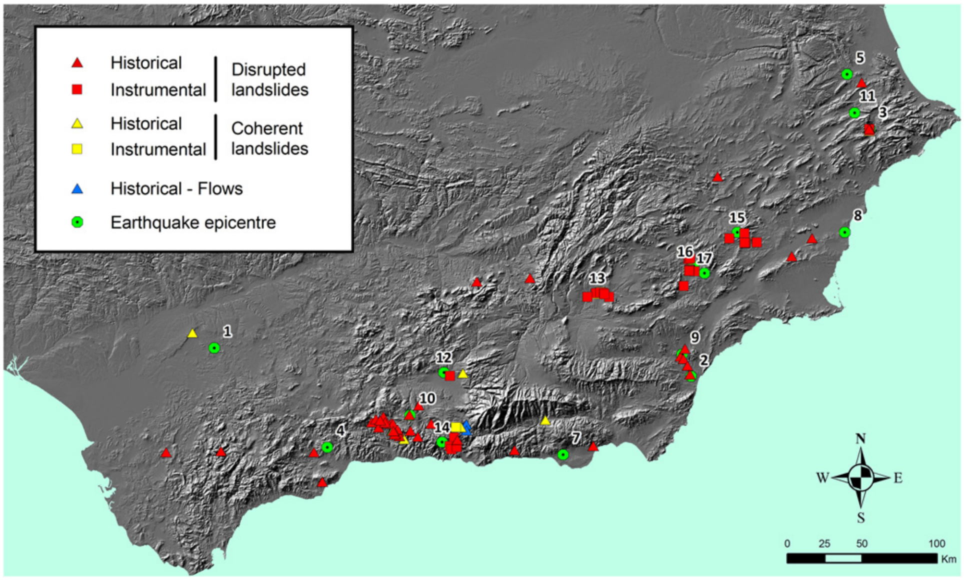

Fig. 2. Location of earthquake-induced landslides in the study zone. Green symbols show location of epicenters. Numbers refer to ID column in Table 1. Epicenter location for event 6 is not included in this figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

was out the possibilities of the current research, so it was impossible to identify which one was really induced by the earthquake. In these cases or when multiple small size instabilities of the same typology occur close to each other, landslide in the database refers to the center of the area that includes such geographical zones (these are the above mentioned 23 records of multiple landslides included in the database). This is the case of several landslides related to events ID7–ID10. For even older earthquakes, identified landslides correspond to instabilities that affected buildings (even whole streets in towns) of special importance, allowing their precise location and characterization. Note that if landslide is not recognizable in the zone, then such historical data is not included in the database. For some recent events (ID13–ID15) there was a concentration of small sized landslides of the same typology at some places of reduced dimensions. For these cases, the database contains only a record for these sites.

The database of landslides includes location (as precise as possible, as previously commented), typology (after Cruden and Varnes [35]), material involved and macroseismic site intensity, when available. We realize that this compilation is not complete, this could not be otherwise, since most data were obtained from historical sources, and the incompleteness increases with time since event occurence. Even if dataset is incomplete, this database contains as many data as possible of landslides reported in historical sources (or recognized during in situ, field inventories for the more recent events) and provides a first look of the relative abundance of typologies of landslides, their size and other physical properties, of great interest for the study of this phenomenon.

Landslides have been classified following the simplified groups defined by Keefer [2]: disrupted landslides (falls and disrupted slides), coherent landslides (slides) and flow and lateral spreading (Fig. 2). Fig. 3 presents histograms showing the frequency of instabilities according to this criterion. We use the terms “soil” and “rock” to describe the characteristic of the intact material in the same sense as this author. From this figure, most data correspond to falls in rock or soils, depending on the nature of materials in the area affected by the quake, or slides in soils that disorganize as motion of unstable mass progress. They represent almost 80% of the instabilities characterized. Rock/soil falls are characterized by involving, in general, small blocks of rock/soil (<1 m^3). In most

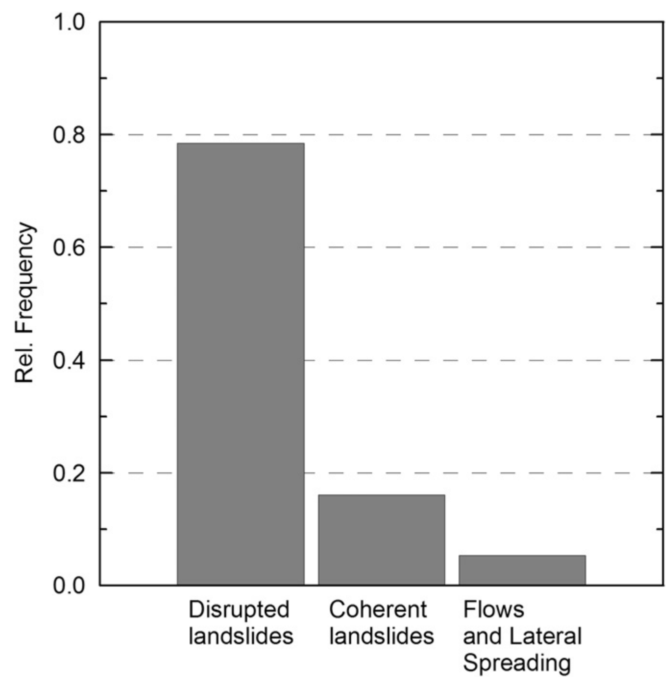

Fig. 3. Relative frequency of landslide typologies in the database.

areas, they are blocks of material delimited by pre-existing planes of weakness (bedding, foliation, joints, fault planes, etc.). They are frequent along steep slopes on rocks and river valleys deeply excavated on low strength materials (marls, clays, alluvial sediments). At some places affected by events ID15 and ID17, a layer of fractured limestone and/or calcarenites exists on top of slopes. Most falls induced by these events correspond to blocks of these materials detached from their original position during the earthquake. Disrupted slides are common in soils. They are frequent along river banks and affect weathered material slopes and terraces.

Coherent landslides are less common (about 15%). They are slightly more frequent during historical than during instrumental events. This may be due to the greater severity of shaking during historical events: usually, both magnitude (M_w) and intensity (I_{max}) are higher for such events. This severity would allow higher levels of peak values of ground motion (ground acceleration, Arias Intensity, etc.), needed for inducing such typology of landslides [36,37].

Although some examples of coherent landslides have been recognized on rocky materials, most of them occur in soils. Usually, they are slumps or rotational slides in soils. Surface of rupture is deep (> 5 m) and, in some extreme cases, it can reach about 15–30 m below ground surface. When affecting rocky materials, they are frequently translational slides. Rupture surface usually coincides with the contact among well cemented, rocky material and plastic, soil-like, underlying material. In such cases, rupture surface is shallow (between 2 and 4 m). Flows and lateral spreading are even less frequent in the database, related to historical events and usually affect marls or soil-like formations.

4. Landslide distribution and seismic parameters

The earthquakes for which landslides could be recognized are characterized by moderate to low magnitude, with the only exception of the 1755 Lisbon earthquake, I_{max}=X, estimated epicentral intensity I_o=XI–XII [38]. Most historical events are characterized by moment magnitudes comprised between 6.0 and 7.0, and epicentral intensities ranging from VII to X (EMS-98 scale, used henceforth). Meanwhile, characteristics of recent events are more homogeneous. Their magnitudes range between 4.7 and 5.0, and only epicentral macroseismic intensities show some dispersion (degree VII–VIII for the former events in this group and V–VI for the more recent ones).

A first analysis has been made considering the site intensity at each place where landslides occurred. This method for measuring severity has the advantage of taking into account possible site-effects that could increase local ground motion severity. Fig. 4 shows the resulting distribution. For this figure, data in mid-range intensities (i.e., VII–VIII or VIII–IX) have been added to data in the lower range. Disrupted landslides (falls and disrupted slides) are frequent for low to moderate intensities (V–VI), while coherent landslides are predominant in the moderate to severe range of intensities. This is in agreement with previous results, which show the fact that the ground motion severity (expressed in Arias intensity terms) needed to induce coherent landslides is greater than for disrupted ones [37]. For both landslide typologies, degree V seems to be the minimum required intensity for occurring in the Betic Cordillera. Note that no attempt is made to estimate site intensity from the occurrence/absence of instabilities, but the minimum intensity required to occur.

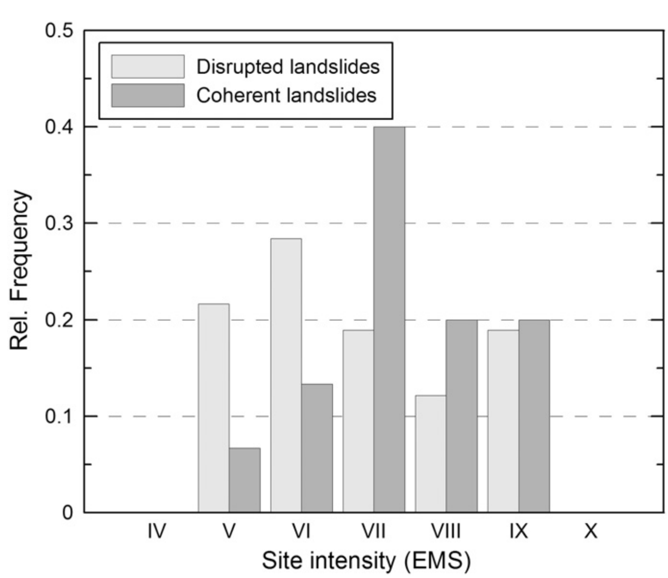

Fig. 4. Distribution of landslide typologies as a function of site intensity.

For the analysis of seismic hazard scenarios and planning, a starting point in most studies is the recognition of patterns of distribution of landslides against the severity of shaking. This is usually accomplished by means of plots of "area affected by landslides" or "maximum distance of occurrence" versus size (magnitude or macroseismic intensity) of events. Based on data from 40 earthquakes around the world, Keefer [2] proposed that there are limiting distances beyond which no landslides are recognized. Additionally, he proposed that there is a magnitude-threshold for causing landslides, which varies depending on the typology: 4.0 for disrupted landslides, 4.5 for coherent landslides and 5.0 for lateral spreading and flows. In a complementary work, where Keefer's database is increased with data from 36 additional worldwide earthquakes, Rodríguez et al. [39] suggested a slight modification in the relationship among "area affected by landslides" and earthquake magnitudes, to account for new available data. Data gathered by other authors confirm the validity of these relationships [40–45], even though outliers frequently appear. Although such relationships are based on earthquake magnitude, some authors point out the interest of using macroseismic intensity for such studies, because it can take into account possible variations in the severity of shaking that could occur within the locus defined by the distance obtained from magnitude [39,46].

For this study, we have analyzed this relationship but using epicentral intensity (I_o). Fig. 5 plots epicentral distances at which each single landslide (disrupted and coherent) occurred versus epicentral intensity (I_o) of causative event. Due to the low number of flows and lateral spreads, the corresponding analysis could not be accomplished for these kinds of landslides. Moreover, we use epicentral distances instead of fault-rupture distances because the causative faults are unknown.

In general, maximum observed distances increase as intensity does, although some breaks to this pattern can be observed for several degrees of intensity, likely linked to the incompleteness of database. The numerical relationship between maximum observed distance of occurrence of a given typology of landslide and epicentral macroseismic intensity of event has been studied. For such purpose, several forms of regression curves have been employed. Among them, the power-law gave the best fit. The resulting regression curves are (Fig. 5):

$$\ln(D_{\text{disrupted}}(\text{km})) = -0.91(\pm 0.18) + 2.04(\pm 0.09)\ln(I_o) \quad (3)$$

$$\ln(D_{\text{coherent}}(\text{km})) = -0.12(\pm 1.11) + 1.68(\pm 0.55)\ln(I_o) \quad (4)$$

The correlation coefficients (ρ^2) are 0.99 (disrupted landslides) and 0.90 (coherent landslides). These relationships were obtained discarding the distance values for the XI–XII epicentral intensity value. Distances computed with both relationships appear as a reasonable initial estimation of maximum expected distances for earthquakes occurring within the continental zone of the Betic cordillera, and of similar characteristics to that used for obtaining the relationship: shallow and moderate to high epicentral intensity (I_o=V–IX–X).

There is a gap of earthquakes having epicentral intensities of degree X to XI–XII in the Betic Cordillera, with the only exception of the 1755 Lisbon earthquake, so we have excluded data from this event in computing Eqs. (3) and (4). Source area of this event is the Azores–Gibraltar zone, characterized by very low intensity attenuation [47]. This translates into very large distances (> 600 km). On the contrary, the continental zone of the Betic Cordillera is characterized by medium to high attenuation, and observed epicentral distances are comparatively small when compared (less than 45 km

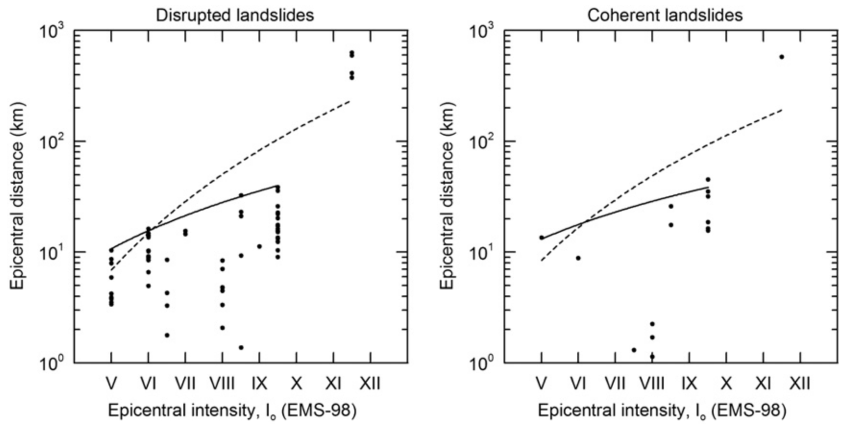

Fig. 5. Epicentral distances for landslides versus epicentral intensity of event. Solid line: regression fit of extreme distances in the intensity range V–IX–X; dash line: regression fit of extreme distances for the intensity range V–XI–XII. Each point in the figure represents a record in the database.

for I_o=IX–X). This is partially in disagreement with findings of Keefer [2], who used data from very different areas, and found no effect of attenuation in his database. Because these very distant data come from a single event, any conclusion drawn should be considered with caution.

Although events similar to the Lisbon 1755 earthquake are not frequent, they appear to occur periodically in the same area. Sandy 'turbidity' deposits induced by submarine gravity slides prove that recurrence periods might be of the order of 1000–2000 years [48–50]. If we include them, the resulting relationships are (see Fig. 5)

$$\ln(D_{\text{disrupted}}(\text{km})) = -4.88(\pm 3.61) + 4.23(\pm 1.48)\ln(I_o) \quad (5)$$

$$\ln(D_{\text{coherent}}(\text{km})) = -3.91(\pm 4.02) + 3.75(\pm 1.89)\ln(I_o) \quad (6)$$

The correlation coefficients (ρ^2) are 0.73 (disrupted landslides) and 0.66 (coherent landslides). Again, these equations are only valid for the study zone, including events from both the Azores-Gibraltar and continental area of the Betic cordillera, and for EMS-98 intensities in the V–XI–XII range

Fig. 6 shows data in the database versus event magnitude (M_w) together with the maximum epicentral distance relationships proposed by Keefer [2]. Note that we have represented all identified instabilities with epicentral distances greater than 1 km instead of the only one occurring at the maximum observed distance for each event. Two zones may be delineated in this figure, both for disrupted and coherent landslides, with a magnitude of 5.0 being the approximate limit between them. Epicentral distances to landslides induced by events with magnitudes above this threshold value lay below the limit distance defined by Keefer [2], irrespective of the typology of the landslide. It may be related with the incompleteness of the used database, although other factors (as the susceptibility of slopes of the areas affected or precedent rain accumulated before earthquake occurrence) may also play an important role. On the contrary, landslides induced by events of lower magnitude may occur well above the limiting distances, in spite of such incompleteness. It is important to point out that, for some events, all instabilities occurred at distances greater than the limiting distances. Although, as previously commented, some uncertainties may exist about magnitude/location of historical events (i.e., $M_w > 5.0$), this is not the case for the more recent ones, where variation of assigned magnitudes is minimal and the error of location is also small (most distant data correspond to instabilities induced by recent events ID13, ID15 and ID17). In the light of these data, as well as other data published by other authors [39–44,51] including data for magnitudes (M_s/M_w) ranging from 3.8 to 6.0, it seems that susceptibility of slopes plays an important role in the occurrence of instabilities [36], and that the use of currently proposed maximum distances for low to moderate magnitudes might give rise to a underestimation of real distances affected by the occurrence of this geotechnical problem. Evidently, the use of a more extensive database, including worldwide data, will help to redefine an overall relationship for maximum distances in the low to moderate magnitude range. Anyway, obtained results in this work are only a case study for the Betic Cordillera, showing this distinctive behavior.

Another analysis has considered the area affected by landsliding in relation with event magnitude (Fig. 7). The computed area corresponds to the surface of a smooth curve that encloses landslides induced by each event. Note that this was carried out only for those events with at least three identified landslides (with the exception of the 1755 Lisbon earthquake, which is not included in this analysis due to the lack of data in N Africa). As widely quoted previously, the database is incomplete for most events, so the computed areas certainly underestimate the real surface affected.

Two events are characterized by very small areas in Fig. 7. Both occurred inland and far from the coast. The first is a historical earthquake (ID3, Alcoy, 1620), where information available is very scarce and concentrates in well documented landslides in the urban area that gives name to this event (Alcoy), but no data exist about other areas that were also likely to have been affected by landsliding [9]. The second event (ID16, Bullas earthquake, 2002) occurred in a rather flat area, and known landslides occurred only to the S of the epicenter, in areas where angle of slopes and state of materials allow the occurrence of instabilities (asymmetry of relief around epicentral area).

The remaining events are characterized by areas that are close to the upper bounds proposed by other authors [2,39]. The events of smaller magnitude (ID9 and ID15) are outliers for these relationships. Although some uncertainty exists about the real magnitude of historical event 9, this is not the case for the other event.

These results are partially in disagreement with the results presented in Fig. 6. Although large distances in this figure could lead one to expect more earthquakes with large areas, this does not occur because for several events the epicenter is located outside of the area where landslides have be identified (Fig. 2), increasing the corresponding distances landslide-epicenter but not the affected area. This is partially due to incompleteness of the database for some events, especially those occurring during historical times, and partially due to intrinsic characteristics of the areas affected (landslides do not occur on flat areas and concentrate along the existing areas with some relief, like river banks or small mounts, as in the events ID16 and ID17, the more recent ones and where database can be considered as complete).

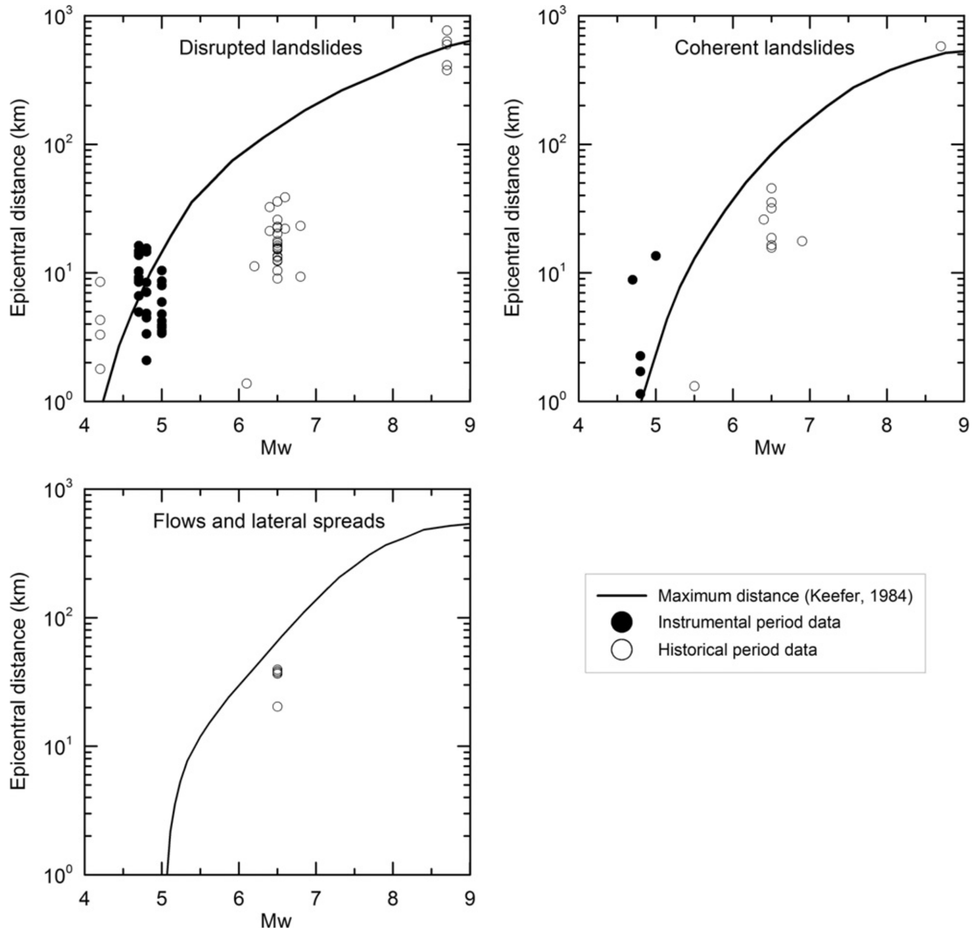

Fig. 6. Epicentral distances for seismically-induced landslides in the Betic Cordillera versus moment magnitude.

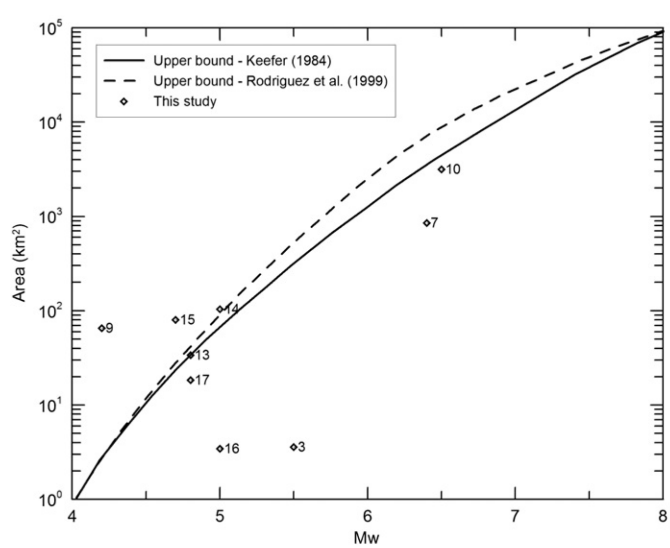

Fig. 7. Area affected by seismic-induced landslides in the Betic Cordillera. Numbers refer to event ID (Table 1).

5. Summary

In this paper we have presented results derived from a database that includes all landslides that could be located and characterized, and were induced by earthquakes, in the Betic Cordillera. Most earthquakes are characterized by moderate to low magnitude ($M_w < 7.0$) and shallow events.

Most landslides ($\approx 80\%$) are classified as falls and disrupted ones (sensu Keefer, [2]), whereas lateral spread and flows are rare in this area. Disrupted landslides usually comprises earth/rock falls and slides in soils that disorganize as movement progresses, and are frequent on steep slopes on rocky materials, and along deeply incised valley, eroded by rivers, and along slopes on weathered materials and terraces (low strength materials) . Coherent landslides are mainly slides in earth/rock, with the surface of rupture frequently located at great depths (5 m or more). This dataset, although incomplete, represents a step forward in the knowledge of this phenomenon in the Betic Cordillera.

These data were used for establishing new relationships, valid initially only for this area, between maximum distance of occurrence of landslides versus earthquake epicentral intensity, with resulting high correlation coefficients for both, disrupted and coherent landslides, when data include events in the range V–IX–X. When the only event with intensity XI–XII is included, the resulting correlation coefficients are lower, although acceptable as a starting point for preliminary regional analyses of seismically-induced landslides hazard studies in the Betic Cordillera.

When considering magnitude (M_w) of events and epicentral distances to landslides, it is observed that they can occur at long distances (>10 km) for events of low magnitude (≤ 5.0), irrespective of the typology of the landslide. It is important to note that most data in this range occur at distances greater than those predicted by pioneering Keefer's relationships [2]. Even there are some earthquakes for which all induced landslides occur at greater distances than these relationships. These instabilities always occurred at places where susceptibility of slopes is high, which likely contributed decisively to landslide occurrence. For events of magnitude greater than 5.0, observed epicentral distances to landslides are well constrained by Keefer's curves [2].

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Appendix A

[A1] P. Gentil (1989). El riesgo sísmico en Sevilla, Serie Arquitectura No. 11, Publicaciones de la Universidad de Sevilla, Sevilla, 1989.

[A2] Instituto Geográfico Nacional. Sismicidad histórica del reino de Granada (1487–1531), IGN, Madrid, 1995.

[A3] IGME. Mapa geotécnico y de riesgos geológicos para la ordenación urbana de Alcoy. Mapa de riesgos geológicos E:1/25.000, 1/2.500, 1/1.000. Memoria. Ministerio de Industria y Energía, Madrid, 1985.

[A4] J.A. Dávila. Evolución urbana de Alcoy (siglos XIII–XVIII). Excmo. Ayuntamiento de Alcoy, Alcoy, 1990.

[A5] F. Vidal. Sismotectónica de la región Béticas–Mar de Alborán. Tesis doctoral. Universidad de Granada, Granada, 1986.

[A6] Xatired, 2009, 〈http://www.xatired.com/laciutat/2003/102003/terremotos.htm〉.

[A7] J.M. Martínez. Los efectos en España del terremoto de Lisboa (1 de noviembre de 1755). Monografía 19, Ministerio de Fomento, Dirección General del Instituto Geográfico Nacional, Madrid, 2001.

[A8] J.A. Larramendi (1829). Memoria y relación circunstanciada de los estragos que la terrible catástrofe de los terremotos de 21 de marzo y siguientes, principalmente el del Sábado Santo 18 de abril hasta el presente día, han causado en Torrevieja y demás pueblos de la gobernación de Orihuela y sus inmediaciones, en la ciudad de Murcia, y algunos pueblos de la provincia de este nombre, Imprenta Real, Madrid, 1829.

[A9] F. Rodríguez de la Torre. Los terremotos alicantinos de 1829. Instituto de Estudios Alicantinos, Excma. Dip. Provincial de Alicante, Alicante, 1984.

[A10] C. Prado. Los terremotos de la provincia de Almería. Revista Minera XIV (1863), vv.pp.

[A11] C. Prado. Terremotos en la provincia de Almería. Escenas Contemporáneas I (1863), 385–386.

[A12] E. Fernández Bolea. Los terremotos de 1863 en la comarca del levante almeriense. Espiral–Cuadernos del profesorado 2 (2009), 27–40.

[A13] D. Orueta y Duarte. Informe sobre los terremotos ocurridos en el sud de España en diciembre de 1884 y enero de 1885, Imprenta F. Muñoz, Málaga, 1885.

[A14] M. Fernández Castro, J.P. Lasala, D. Cortázar, J. Gonzalo y Tarín. Terremoto de Andalucía: Informe de la comisión nombrada para su estudio dando cuenta del estado de los trabajos en 7 de marzo de 1885. Imp. M. Tello, Madrid, 1885.

[A15] Instituto Geográfico Nacional. El terremoto de Andalucía del 25 de diciembre de 1884, Publicaciones IGN, Madrid, 1980.

[A16] A. García Maldonado. Terremotos y solidaridad. Granada-Málaga 1884–1885, Excma. Dip. Provincial de Málaga, Málaga, 1985.

[A17] A. Gómez Ruiz. Güevéjar: de alquería musulmana a municipio de la Vega de Granada, Excma. Dip. Provincial de Granada and Ayto. de Güevéjar, Granada, 1985.

[A18] IAG, 2003, 〈http://www.ugr.es/~iag/divulgacion/boletines/b2.html〉.

[A19] Instituto Geográfico Nacional. Nota informativa preliminar de los sismos de Orce y Galera, Junio 1964, Publicaciones IGN, Madrid, 1964.

[A20] Diario Ideal, Edition of June 10, 1964. Granada.

[A21] Diario Ideal, Edition of June 26, 1984. Granada.

[A22] Diario Ideal, Edition of June 27, 1984. Granada.

[A23] T. Rodríguez Estrella, F. Navarro Hervás. Desprendimientos y vuelcos en laderas, desencadenados por sismicidad, en la cuenca de Mula (Murcia). Espacio Natural y dinámicas territoriales. Libro Homenaje al Dr. Jesús García Fernández. Universidad de Valladolid, Valladolid, 2000, pp. 171–181.

References

[1] Newmark NM. Effects of the earthquakes on dams and embankments. Geotechnique 1965;15:139–60.
[2] Keefer DK. Landslides caused by earthquakes. Geological Society of America Bulletin 1984;95:406–21.
[3] ISSMGE. Manual for zonation on seismic geotechnical hazards. Tokyo: Technical Committee for Earthquake Geotechnical Engineering, TC4, International Society for Soil Mechanics and Geotechnical Engineering. The Japanese Geotechnical Society; 1999.
[4] Jibson RW, Harp EL, Michael JA. A method for producing digital probabilistic seismic landslide hazard maps. Engineering Geology 2000;58:271–89.
[5] Miles SB, Keefer DK. Evaluation of CAMEL—comprehensive areal model of earthquake-induced landslides. Engineering Geology 2009;104:1–15.
[6] García Mayordomo J. Riesgo sísmico en la cuenca de Alcoy (Alicante). Aproximación a una zonificación sísmica. Tesis de Máster. Universidad Complutense de Madrid, Madrid; 1998.
[7] García Mayordomo J. Zonificación sísmica de la cuenca de Alcoy mediante un sistema de información geográfica. 1er Congreso Nacional de Ingeniería Sísmica, Murcia, 1999. p. 443–50.
[8] Delgado J, Peláez JA, Tomás R, Estévez A, López Casado C, Doménech C, et al. Susceptibilidad a movimientos de ladera inducidos por terremotos en Alcoy (Alicante) y sectores adyacentes. Geotemas 2004;6:285–8.
[9] Delgado J, Peláez JA, Tomás R, Estévez A, López Casado C, Doménech C, et al. Incertidumbres en la determinación de la susceptibilidad a movimientos de ladera inducidos por terremotos en Alcoy (Alicante). In: Conesa C, Álvarez Y, Martínez-Guevara JB, editors. Medio Ambiente, recursos y riesgos naturales. Análisis mediante tecnología SIG y Teledetección. Murcia: Universidad de Murcia; 1994. p. 165–75.
[10] Delgado J, Peláez JA, Tomás R, Estévez A, López Casado C, Doménech C, et al. Evaluación de la susceptibilidad de las laderas a sufrir inestabilidades inducidas por terremotos: Aplicación a la cuenca de drenaje del río Serpis (provincia de Alicante). Revista de la Sociedad Gelógica de España 1996;19:197–218.
[11] Rodríguez Peces MJ, García Mayordomo J, Azañón JM, Jabaloy A. Evaluación de inestabilidades de ladera por efecto sísmico en la cuenca de Lorca (Murcia): implementación del método de Newmark en un SIG. Boletín Geológico y Minero 2008;119:459–72.
[12] García Mayordomo J, Rodríguez Peces MJ, Azañón JM, Insua Arévalo JM. Advances and trends on earthquake-triggered landslide research in Spain. I INQUA-IGCP International Workshop on Earthquake Archaeology and Palaeoseismology, Cádiz; 2009. p. 28–31.
[13] Rodríguez Peces MJ, García Mayordomo J, Azañón JM. Comparing Newmark's method at regional, sub-regional and site scales: seismically-induced La Paca rock-fall case (Murcia, SE Spain). In: Proceedings of the eighth international workshop on seismic microzoning and risk reduction, Aguadulce; 2009. p. 125–33.
[14] Jiménez Pintor J, Azor A. El deslizamiento de Güevéjar: estudio de una inestabilidad desencadenada por terremotos. Geogaceta 2006;40:287–90.
[15] De Mets C, Gordon RG, Argus DF, Stein S. Effect of recent revisions to the geomagnetic reversals time scale on estimates of current plate motions. Geophysical Research Letters 1994;21:2191–4.
[16] Sanz de Galdeano C. Geologic evolution of the Betic Cordilleras in the Western Mediterranean, Miocene to the present. Tectonophysics 1990;172:107–19.
[17] Peláez JA, López Casado C. Seismic hazard estimate at the Iberian Peninsula. Pure and Applied Geophysics 2002;159:2699–713.
[18] Peláez JA, Delgado J, López Casado. C. A preliminary probabilistic seismic hazard assessment in terms of Arias intensity in southeastern Spain. Engineering Geology 2005;77:139–51.
[19] Sanz de Galdeano C, López Casado C, Delgado J, Peinado MA. Shallow seismicity and active faults in the Betic Cordillera. A preliminary approach to seismic sources associated with specific faults. Tectonophysics 1995;248: 293–302.
[20] Mezcua J, Rueda J, Martínez Solares JM. Seismicity of the Ibero-Maghrebian region. In: Mezcua J, Udías A, editors. Seismicity, seismotectonics and seismic risk of the Ibero-Maghrebian region. Madrid: Instituto Geográfico Nacional; 1991. p. 17–28.

[21] Buforn E, Sanz de Galdeano C, Udías A. Seismotectonics of the Ibero-Maghrebian region. Tectonophysics 1995;248:247–61.

[22] Chung WY, Kanamori H. Source process and tectonic implications of the Spanish deep-focus earthquake of March 29, 1954. Physics of the Earth and Planetary Interiors 1976;13:85–96.

[23] Buforn E, Udías A, Madariaga R. Intermediate and deep earthquakes in Spain. Pure and Applied Geophysics 1991;136:375–93.

[24] Mezcua J, Martínez Solares JM. Sismicidad de la region Ibero.Maghrebí. IGN Report, Madrid; 1983 (updated).

[25] Martínez Solares JM, Mezcua J. Catálogo sísmico de la Península Ibérica (880 a.C.-1900). Madrid: IGN; 2002.

[26] Bakun WH, Wentworth CM. Estimating earthquake location and magnitude from seismic intensity data. Bulletin of the Seismological Society of America 1997;87:1502–21.

[27] Bakun WH, Wentworth CM. Erratum to ''Estimating earthquake location and magnitude from seismic intensity data''. Bulletin of the Seismological Society of America 1999;89:557.

[28] Rueda J, Mezcua J. Near-real-time seismic moment-tensor determination in Spain. Seismological Research Letters 2005;76:455–65.

[29] Rueda J, Mezcua. J. Sismicidad, sismotectónica y peligrosidad sísmica en Galicia. Madrid: IGN; 2001.

[30] Rueda J, Mezcua J. Estudio del terremoto de 23 Septiembre de 2003, Pego (Alicante). Obtención de una relación mbLg-MW para la Península Ibérica. Revista de la Sociedad Geológica de España 2002;15:159–73.

[31] Mezcua J, Rueda J, García Blanco RM. Reevaluation of historic earthquakes in Spain. Seismological Research Letters 2004;75:75–81.

[32] Instituto Geográfico Nacional. Análisis sismotectónico de la Península Ibérica, Baleares y las Islas Canarias. Madrid: IGN; 1992.

[33] Espinar M, Quesada JJ, Morcillo JD. Terremotos en Granada (siglos XV–XVI). Edificación y sismicidad. Colección Investigación Arráez Editores, Almería; 1994.

[34] López JM. Marinas. Terremotos históricos en las provincias de Alicante y Murcia. Cimbra 1978;156:4–16.

[35] Cruden DM, Varnes DJ. Landslide types and processes. In: Turner AK, Schuster RL, editors. Landslides. Investigation and mitigation. Special Report 247. Transportation Research Board. Washington: National Research Council; 1996. p. 36–75.

[36] Wilson RC, Keefer DK. Predicting areal limits of earthquake-induced landsliding. In: Ziony JI, editor. Earthquake hazards in the Los Angeles region—an earth-science perspective. U.S. geological survey professional paper 1360; 1985. p. 317–45.

[37] Keefer DK, Wilson RC. Predicting earthquake-induced landslides, with emphasis on arid and semi-arid environments. In: Sadler PM, Mortons DM, editors. Landslides in a semiarid environment. Inland Geological Society, vol. 2. Riverside: Southern California Publications; 1989. p. 118–49.

[38] Martínez Solares JM. Los efectos en España del terremoto de Lisboa (1 de noviembre de 1755). Monografía 19, Ministerio de Fomento, Dirección General del Instituto Geográfico Nacional, Madrid; 2001.

[39] Rodríguez CE, Bommer JJ, Chandler. RJ. Earthquake-induced landslides: 1980–1997. Soil Dynamics and Earthquake Engineering 1999;18:325–46.

[40] Papadopoulos GA, Plessa A. Magnitude-distance relations for earthquake-induced landslides in Greece. Engineering Geology 2000;58:377–86.

[41] Prestininzi A, Romeo R. Earthquake-induced ground failures in Italy. Engineering Geology 2000;58:387–97.

[42] Bommer JJ, Rodríguez. CE. Earthquake-induced landslides in Central America. Engineering Geology 2002;63:189–220.

[43] Hancox GT, Perrin ND, Dellow GD. Recent studies of historical earthquake-induced landsliding, ground damage, and MM intensity in New Zealand. Bulletin of the New Zealand Society for Earthquake Engineering 2002;35:59–95.

[44] Keefer DK. Investigating landslides caused by earthquakes—a historical review. Surveys in Geophysics 2002;23:473–510.

[45] Porfido S, Esposito E, Vittori E, Tranfaglia G, Michetti AM, Blumetti M, et al. Areal distribution of ground effects induced by strong earthquakes in the southern Apennines (Italy). Surveys in Geophysics 2002;23:529–62.

[46] Perkins DM. Landslide hazard maps analogues to probabilistic earthquake ground hazard maps. In: Cruden D, Fell R, editors. Landslide risk assessment. Rotterdam: Balkema; 1997. p. 327–32.

[47] López Casado C, Molina S, Delgado J, Peláez JA. Attenuation of intensity with epicentral distance in the Iberian Peninsula. Bulletin of the Seismological Society of America 2000;90:34–47.

[48] Grevemeyer I, Kaul N, Gutscher MA. The thermal structure of the Gibraltar subduction zone from new heat flow measurements and finite-element modeling, Abstracts of the First European Geosciences Union Meeting, Nice; 2004.

[49] Gutscher MA. What caused the great Lisbon earthquake? Science 2005;305: 1247–8.

[50] Gutscher MA. Destruction of Atlantis by a great earthquake and tsunami? A geological analysis of the Spartel Bank hypothesis Geology 2005;33:685–8.

[51] Rodríguez CE. Earthquake-induced landslides in Colombia, ECI Conference on Geohazards, Lillehammer; 2006, paper 38.

[52] Stich D, Ammon CJ, Morales J. Moment tensor solutions for small and moderate earthquakes in the Ibero-Maghreb region. Journal of Geophysical Research 2003, doi:10.1029/2002JB002057.