Engineering Geology 123 (2011) 204–213

Contents lists available at SciVerse ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

On far field occurrence of seismically induced landslides

J. Delgado [a,*], J. Garrido [b], C. López-Casado [c], S. Martino [d], J.A. Peláez [e]

[a] Dpt. Ingeniería de la Construcción, Universidad de Alicante, Ap. Correos 99, 03080 Alicante, Spain
[b] Dpt. Ingeniería Civil, Universidad de Granada, Campus Fuentenueva, Av. Severo Ochoa s/n. 18071 Granada, Spain
[c] Dpt. Física Teórica y del Cosmos, Universidad de Granada, Campus Fuentenueva, Av. Severo Ochoa s/n. 18071 Granada, Spain
[d] Dpt. Scienze della Terra, Università di Roma, La Sapienza, P.le Aldo Moro 5, 00185 Roma, Italy
[e] Dpt. Física, Campus Las Lagunillas, Universidad de Jaén, 23071 Jaén, Spain

ARTICLE INFO

Article history:
Received 15 November 2010
Received in revised form 24 August 2011
Accepted 27 August 2011
Available online 9 September 2011

Keywords:
Landslide
Earthquake
Magnitude
Macroseismic intensity
Maximum distance

ABSTRACT

Earthquakes may induce landslides at large distances from the epicentral area. In the last two decades, there have been many studies of this phenomenon to determine the causes that contribute to the occurrence of landslides at very long distances from earthquake epicenter. In this study, which is based on previously published works, a worldwide database comprising 270 earthquakes, including 150 during the instrumental period, was compiled to analyse the features of those landslides that occur at much further distances than maximum expected distances. From the analysis of the compiled data, it was observed that susceptible slopes can be grouped into five broad geological categories: jointed rock, marly–clayey (cohesive) soils, granular alluvial and/or colluvial sediments, volcanic soils, and residual soil slopes. These categories were equally likely to be associated with far field disrupted landslides, whereas far field coherent landslides were more frequent on cohesive soil slopes. Other factors, along with slope susceptibility may also contribute to far field landslides and increase the size of the area affected. Among these factors, site effects, antecedent rain and occurrence of seismic series have been cited. The analysis of available data also showed that for events of the same magnitude, far field disrupted landslides may occur at greater distances than coherent ones. The same database has also been employed to determine, for the first time, the upper bound curves for the maximum observed epicentral distances of several types of landslides and the maximum area observed to be affected by landslides, both based on the epicentral intensity of the events.

1. Introduction

The stability of a slope can be regarded as a balance between resisting and driving forces that act on it. When an earthquake occurs, ground motion acts as an additional driving force element on the slope, thereby favoring its instability (Hoek and Bray, 1981; Duncan and Wright, 2005). The greater the energy of the earthquake, the greater the disturbance created and at longer distances. As a consequence, the maximum distance of the occurrence of disturbances increases as the energy (expressed either as Arias intensity, magnitude or macroseismic intensity) of the earthquake increases.

In a pioneering study, Keefer (1984) presented a set of upper bound curves for the maximum distance of seismically induced landslides as a function of event magnitude, which was based on a dataset of 40 worldwide earthquakes. He grouped the types of landslides into three simple categories: disrupted slides and falls, coherent slides, and lateral spread and flows. For each group, he also proposed magnitude thresholds for earthquakes to induce landslides; the minimum magnitude of an earthquake that would cause disrupted landslides would be 4.0, with magnitudes 4.5 for coherent slides and 5.0 for flows and lateral spreads. Notwithstanding, he also indicated that because landslides can be triggered by several causes, it would not be uncommon to find landslides induced by earthquakes of lower magnitudes when shaking occurred concurrently with other triggering factors, or when failure of the slope was imminent before the earthquake. In this sense, several examples of low magnitude induced landslides have been reported in the literature (Keefer, 1984; Rodríguez et al., 1999; Papadopoulos and Plessa, 2000). Later studies by these and other researchers showed that the proposed upper bounds are appropriate in most cases, although some outliers started to appear with each new dataset (Rodríguez et al., 1999; Prestininzi and Romeo, 2000; Bommer and Rodríguez, 2002; Hancox et al., 2002; Keefer, 2002; Rodríguez, 2006; Delgado et al., 2011).

A review of the characteristics of these outliers is reported in this study. For this purpose, a new worldwide database based on previously published work was compiled and the data was analyzed, highlighting the existence of significant outliers and assessing their features in terms of both the materials involved and the most likely triggering factors. In addition, new upper bound curves are proposed

* Corresponding author. Tel.: +34965903400x2122; fax: +34965909862.
E-mail addresses: jose.delgado@ua.es (J. Delgado), jega@ugr.es (J. Garrido), clcasado@ugr.es (C. López-Casado), salvatore.martino@uniroma1.it (S. Martino), japelaez@ujaen.es (J.A. Peláez).

0013-7952/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.enggeo.2011.08.002

based on the use of the macroseismic maximum intensity as a way of measuring earthquake ground motion severity, which is useful for those areas where a long seismic and documented history are available. The resulting curves may be considered complementary to those based on earthquake magnitude that were previously proposed, and are not a substitute when instrumental data are employed.

2. State of the art

Several authors have addressed the problem of seismic induced landslides. There is a set of possible causes that may act alone or in combination to explain the occurrence of seismically induced landslides at long distances from the seismic focus, that in some cases exceed distances predicted by the maximum distance curves proposed by Keefer (1984).The first possible cause for some outliers is that the earthquake is part of a seismic series (Rodríguez et al., 1999; Papadopoulos and Plessa, 2000; Keefer, 2002). Shaking produced by initial events might weaken the slope (by fracturing materials, opening joints in rock masses, reducing cohesion in soils, increasing pore-water pressure in soil slopes, etc.), and when a new earthquake occurs, the slope may fail even after a very low level of shaking. This seems to be the probable cause of an example from Greece (Papadopoulos and Plessa, 2000).

In other cases, outliers may occur because they are located in susceptible areas that are prone to landslides. In the case of rocky slopes, Harp and Noble (1993) mentioned six properties of rock mass discontinuities (except for weak or massive rocks, the properties of intact rock do not directly control the stability of rock mass): the number of fractures per unit volume, the number of joint sets, roughness, weathering of joint walls, pore-water pressure and joint aperture, the latter being the most important in controlling the occurrence of rock falls. In the case of soil slopes, residual soils and/or saturated (sensitive) cohesive soils, dry colluviums or unconsolidated alluvial sediments are prone to instability during earthquakes. These materials, combined with relief (steep, rugged areas or along road cuts) or with slopes undercut by erosion constitute conditions where many seismically induced landslides occur most often (Keefer, 2000; Parise and Jibson, 2000; Kazhai and Sitar, 2003).

In addition, environmental factors may contribute to the increased the natural susceptibility of some slopes. Among them, rain is a key factor that alone can trigger many landslides (Záruba and Mencl, 1982; Wieczoreck, 1996; Iverson, 2000). When combined with earthquakes, landslides during or after rain can occur at further distances from the epicenter than when the terrain is dry (Mora and Mora, 1994). This factor probably contributed to failure of the most distant slopes during the 1988 Sanguenay (Canada) earthquake (Lefebvre et al., 1992; Rodríguez et al., 1999).

Finally, another factor that can contribute to the occurrence or frequency of distant landslides is changes in ground motion that increase its severity (site effects). Relief has a notable influence on the propagation of seismic waves, resulting in to zones of amplification/de-amplification of ground motion at certain locations (Bouchon, 1973; Geli et al., 1988; Bouchon et al., 1996; Ashford and Sitar, 1997; Havenith et al., 2003). Meunier et al. (2008) modeled the propagation of waves in a generic ridge-and-valley topography oriented parallel to the hypothetical fault source. Amplification of ground motion was associated with convexities in mountain ridges, such as ridge crests and ridge flank knick points. Zones of maximum amplification were located near to ridge crests for vertically incident waves. As the angle of incidence increased, the maximum shifted progressively into the ridge flanks that faced away from the wave source. This topographical site effect may contribute to the triggering of instabilities during earthquakes at specific locations, as seems to have occurred during the Chi-Chi, Taiwan (September 21, 1999), and Finisterre mountains, Papua New Guinea (October 1993, Mw = 6.7 and 6.9) earthquakes (Meunier et al., 2008).

The effect of step-like slope topography on seismic ground motion was only recently investigated by some authors (Ashford and Sitar, 1997; Bouckovalas and Papadimitriou, 2005; Nguyen and Gatmiri, 2007; Lenti and Martino, 2010; Papadimitriou and Chaloulos, 2010) who used numerical modeling because results from field measurements are difficult to obtain due to the wave scattering that is produced by the step-like slope geometry. These studies demonstrated that step-like slope topography may lead to intense amplification and de-amplification irregularly along the slope, depending on its geometry. Pre-existing landslide masses can also influence the site response directivity, which can produce amplification maxima oriented along the potential sliding direction. But the causes of the directivity phenomena are still unclear because they can be related to a combination of topographic, lithological and structural factors that can re-distribute shaking energy and focus it in site-specific directions (Del Gaudio and Wasowski, 2010).

The interaction of seismic waves with slope can also influence the induced non-linear deformations in the case of both unsheared slopes that were not yet affected by landslide processes, and pre-existing landslide masses, i.e., considering “first-time slides” and “slides on pre-existing shears” (sensu Hutchinson, 1988), respectively (Lenti and Martino, 2010).

A particular case of site effects, not necessarily of the topographical type, is called the “self-excitation process” (Bozzano et al., 2008a, b, 2010). In this case, a preexisting (active or dormant) landslide is excited by the earthquake and the amplification of ground motion induced by the landslide mass may generate a self-triggering process that reactivates the landslide. As these authors demonstrated, the frequency content of the incoming seismic wave field is fundamental to the occurrence of this phenomenon, as it does not take place when the energy, in the frequency range that the landslide mass is able to amplify, is low. This process of self-excitation has been documented for two seismically induced landslides in Italy (Table 1). In both cases, the earthquakes were of moderate magnitude (Mw = 5.8–5.9) and reactivated two large-scale (areas affected of about 1 and 1.5 km^2, respectively) coherent soil slides at epicentral distances greater than 30 km.

3. Data

The database compiled for this study was based on previously published worldwide, country and regional based datasets (Table 2). Usually, data were listed in tables within the papers that presented the corresponding dataset. When this was not the case, and data were presented in a graphical form, the figures were scanned and digitized. In addition, data about landslides induced by single earthquakes were also gathered and included in the database. These recent data are listed in Table 1.

Data from Italy (Prestininzi and Romeo, 2000) were presented in a plot showing all landslides triggered by earthquakes in Italy and not the most distant ones triggered by each event. As a consequence, many data points were landslides induced by the same earthquake. As part of their study, these authors referred to the Italian catalog of seismically induced effects (CEDIT catalog by Romeo and Delfino, 1997); the CEDIT database was consulted using a direct search of landslides, the geographical location of landslides and the magnitudes/intensities of earthquakes within the data tables available in the catalog. Note that most Italian data come from recent events: the Irpinia Mw 6.9 (November 11, 1980) earthquake, the Umbria-Marche Mw 5.8 and 6.0 (September 26, 1997) earthquake and the L'Aquila Mw 5.8 (April 6, 2009) earthquake, which were fortunately included in other collected datasets (Rodríguez et al., 1999; Esposito et al., 2000; Bozzano et al., 2001; Porfido et al., 2007; Blumetti et al., 2009; EMERGEO, 2009; Miccadei et al., 2010).

As in the case of Italian data, a careful revision was performed to avoid duplicated entries in the database. For instance, most data

Table 1
Seismic induced landslides due to recent earthquakes. List includes data from recent papers where a revision of available information for recent/historical earthquakes was done.

Location	Date	Magnitude (Mw)	Depth (km)	Imax	Maximum distance (km)			Area affected (km^2)	Source
					Disrupted	Coherent	Flow		
S Apennines (Italy)	23/07/1930	6.7	–	X	77.5	19	9	–	Esposito et al. (2009)
SW Montefrío (Spain)	24/10/1991	2.6 (mbLg)	5	–	7.9	–	–	–	Garrido (1991)
Umbria-Marche (Italy)	26/09/1997	6.0	5	IX/X	28.9	23.9	15.6	1400	Esposito et al. (2000) Bozzano et al. (2001)
Chi-Chi (Taiwan)	21/09/1999	7.3	33		117	–	–	–	Liao and Lee (2000)
Avaj (Iran)	22/06/2002	6.5	10	IX	54	28	24	3600	Mahdavifar et al. (2006)
Palermo (Italy)	06/09/2002	5.89	10	–	–	50	–	–	Bozzano et al. (2008a) INGV (2004)
Molise (Italy)	31/10/2002	5.78	–	VIII/IX	–	30	–	–	Bozzano et al. (2008b) INGV (2004)
Denaly (Alaska, USA)	03/11/2002	7.9	5	–		300	–	10,000	Jibson et al. (2006)
Colima (Mexico)	22/01/2003	7.6	24	VIII	100	–	–	7945	Keefer et al. (2006)
Boumerdes (Algeria)	21/05/2003	6.8	10	X	24.2	–	–	39	Bouhadad et al. (2004) Harbi et al. (2007) Bouhadad et al. (2009)
Lefkada (Greece)	14/08/2003	6.2	12	VIII	19.5	–	–	–	Papathanassiou et al. (2005)
Niigata (Japan)	23/10/2004	6.6	13.4		18	–	–	390	Wang et al. (2007)
Olyutor (Kamchatka)	20/04/2006	7.6	60	IX		–	–	<6400	Rogozhin et al. (2009)
Aysen (Chile)	21/04/2007	6.2	10	VII	42	–	17	1200	Sepúlveda et al. (2010)
Pisco (Peru)	15/08/2007	8.0	39	VIII	198	198	162	–	INGEMMET (2007) USGS (2009)
Wenchuan (China)	12/05/2008	7.9	19	XI	–	–	–	5700	Sato and Harp (2009)
Iwate-Miyagi (Japan)	14/06/2008	7.2	8	–	–	–	–	600	Yagi et al. (2009)
L'Aquila (Italy)	06/04/2009	5.8	10–12	XI/X	45.2	–	–	–	Blumetti et al. (2009) EMERGEO (2009) Miccadei et al. (2010)
Chile	27/02/2010	8.8	35	–	410	–	–	–	Wick et al. (2010)
Chile aftershock 1	11/03/2010	6.9	–	–	230	–	–	–	Wick et al. (2010)
Chile aftershock 2	11/03/2011	6.7	–	–	220	–	–	–	Wick et al. (2010)

from Costa Rica (Mora and Mora, 1994) were included in the compilation by Bommer and Rodríguez (2002) for the Central American region, and the data about the Umbria-Marche (Esposito et al., 2000) also appeared in the paper by Rodríguez et al. (1999). For this latter event, we retained the data presented by Esposito et al. (2000) and Bozzano et al. (2001), which were specifically obtained for this single event. For the L'Aquila earthquake, a very recent review by Miccadei et al. (2010) was considered here to account for its related seismically induced landslides (the very last Mw>5.5 earthquake that occurred in Italy to date).

The quality of data varies as a function of the date of the earthquake occurrence. For historical events, the locations of epicenters were based on macroseismic data. When the event affected densely populated areas, such as in many areas in Japan, China or Italy, where there is also a rich documentary tradition, the error in identifying the location may be quite low: a few kilometers. As an example, Fig. 1 shows the area affected by three very different, well-documented events that occurred in southern Europe.

Table 2
List of datasets used in the present analysis. Magnitudes are usually Ms for M<7.0 and Mw for M>7.0.

Geographical area	Period covered	Magnitude range	Source
Worldwide	1811–1980	5.2–9.2	Keefer (1984)
Costa Rica	1888–1993	5.2–7.5	Mora and Mora (1994)
Worldwide	1980–1997	5.3–8.1	Rodríguez et al. (1999)
Greece	1650–1995	3.8–7.9	Papadopoulos and Plessa (2000)
Italy	461 BC–1980	4.5–7.5	Prestininzi and Romeo (2000)
Central America	1902–2001	4.6–8.0	Bommer and Rodríguez (2002)
New Zealand	1848–1995	4.9–8.2	Hancox et al. (2002)
USA	1988–1994	4.6–5.7	Keefer (2002)
Colombia	1644–1999	5.0–8.1	Rodríguez (2006) CEREIS (2010)
S Spain	1504–2005	4.2–8.7	Delgado et al. (2011)

The first event presented in Fig. 1 is the February 23, 1887 Ligurian earthquake (Mw = 6.29; INGV, 2004) in northern Italy. In this case, the source was near to the coast but was located inland. Considering the distribution of maximum intensities, the error in the location of the epicenter was probably of the order of 5 km, similar to that computed for instrumentally located events in many areas around the world. This event triggered several landslides, one of them at a very long distance from the epicenter (Figure 1). Unfortunately, the magnitude of this, and all historical events must be estimated indirectly (i.e., from intensity–magnitude relationships), which introduces some uncertainties in the actual value of this seismic parameter.

The second event presented in Fig. 1 is the September 6, 2002, Palermo earthquake (Mw = 5.89; INGV, 2004) that was responsible for a far field reactivation of one landslide 50 km away from the epicenter (within the municipality of Cerda; Bozzano et al., 2010). It is interesting to notice that such a landslide is located very close to another one (Collesano landslide) induced by the March 5, 1823, Sicily earthquake (Mw = 5.9; INGV, 2004). In both cases, the landslides occurred in a very similar geological setting; moreover, the reactivation occurred with a significant time delay (approximately two hours) following the main shock. For the case of the Sicily event, that appears in the database presented by Prestininzi and Romeo (2000), the epicentral distance was computed by the authors of the CEDIT catalog for the above mentioned landslide and clearly consider a double hypothesis of epicenter location, which was reported in the reference seismic catalog (NT4.1 release by GNDT, 1996) and based on the macroseismic field. Thus, the reference epicentral distance appears to be located off-shore, in correspondence with the recognized Tyrrhenyan offshore source (ITGG056 source in the DISS3 seismic source catalog by Basili et al., 2008).

The intensities recorded for the October 31, 2002 Molise earthquake (Mw = 5.78; INGV, 2004) are the third case presented

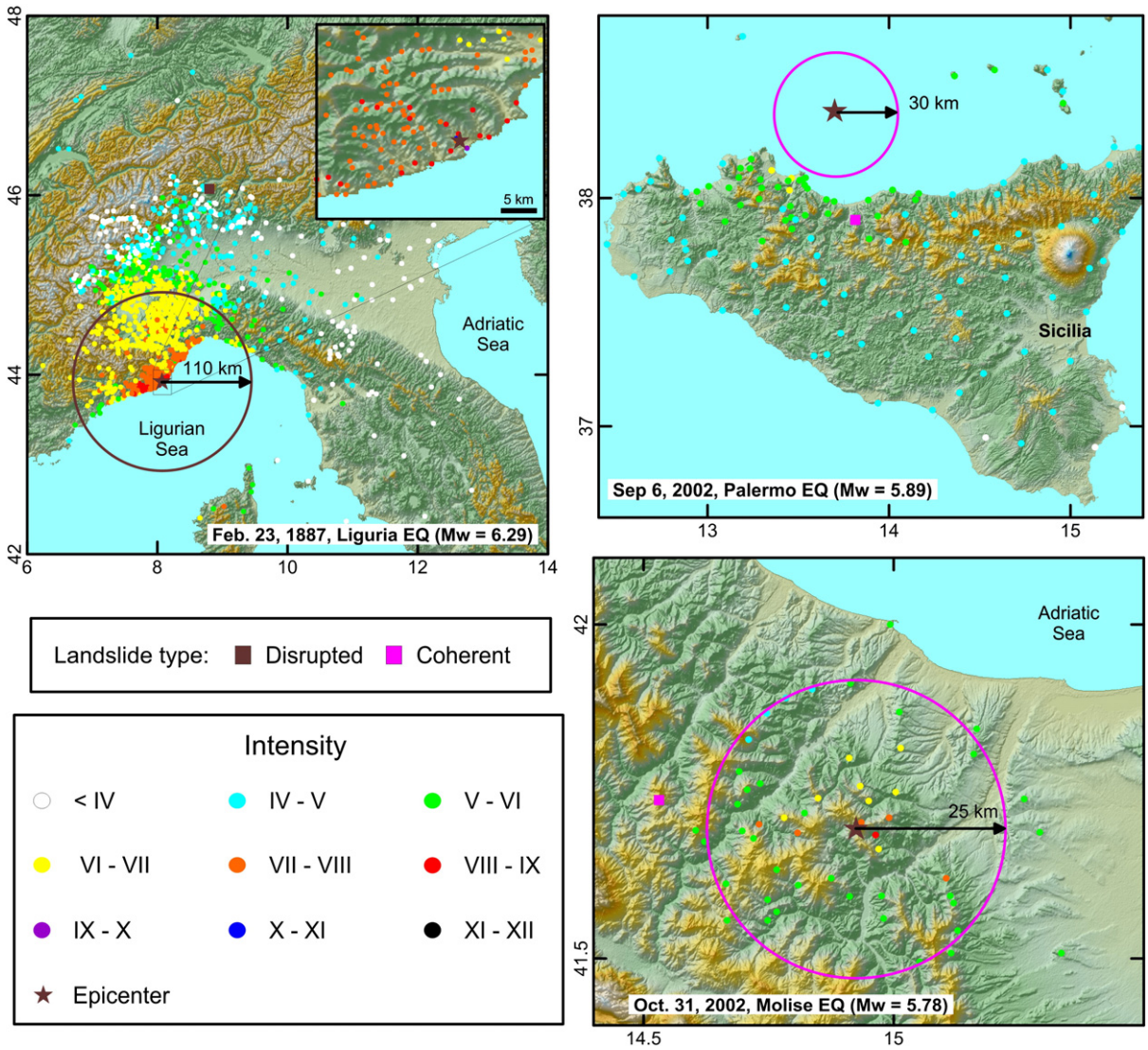

Fig. 1. Intensity maps for the 1887 Liguria, 2002 Palermo and 2002 Molise earthquakes. Location of far field (outliers) induced landslides is also included. Circles represent maximum expected distances for several types of landslides as proposed by Keefer (1984). Intensities for the events after INGV (2004).

(Figure 1). This recent event triggered a very distant coherent landslide, as shown in Fig. 1. This event occurred in very close spatial proximity to another historical earthquake, the July 30, 1627 Gargano earthquake (Mw = 6.73; INGV, 2004), also known as the Capitanata earthquake, which could be precisely located based on the distribution of epicentral intensities. The error in locating the epicenter for this historical event based on macroseismic data is probably in the same range as that of the recent Molise earthquake, which was located based on instrumental records.

The resulting final database contains a total of 270 records. For each event, a set of fields were defined for location (and corresponding error), time of occurrence, size (magnitude and maximum intensity), maximum observed distances of induced landslides and the affected area. A review of seismic parameters (epicentral coordinates, magnitude, etc.) was performed for earthquakes occurring before 1980 so that only recent data would be included. Note that there are many incomplete records, meaning that not all fields defined in the database are known for each earthquake. As a consequence, the total available data for each category of landslide is always lower than the number of records in the database.

A second database was extracted from this worldwide database by filtering out records occurring in the historical period, i.e., data from earthquakes located and characterized from macroseismic data/ground evidence for which uncertainties in magnitude and/or epicenter location might arise. Data included in this new database is characterized by precise location (when reported, error in location is usually less than 5–10 km) and reliable determination of magnitude/intensity of the event. This subset contains a total of 150 records.

4. Analysis of data and discussion

Available maximum distances were plotted against magnitude (Figure 2) and organized according to the three simple landslide type defined by Keefer (1984): disrupted, coherent and flows/lateral spreads. This figure also includes the upper bound curves of maximum distance proposed by Keefer (1984). Note that the very low magnitude event listed in Table 1 was not included in this figure. Most data were well contained by the upper bounds proposed by Keefer (1984), although there was a set of outliers for the disrupted and coherent landslide categories.

It is noticeable that all outliers always occurred in the low to moderate range (M < 7.0 for disrupted and M < 6.0 for coherent landslides), except for data from the November 1, 1755, Lisbon earthquake (estimated Mw = 8.7; Martínez Solares, 2001; Martínez Solares and López Arroyo, 2004). Its source was located offshore, at the Azores–Gibraltar

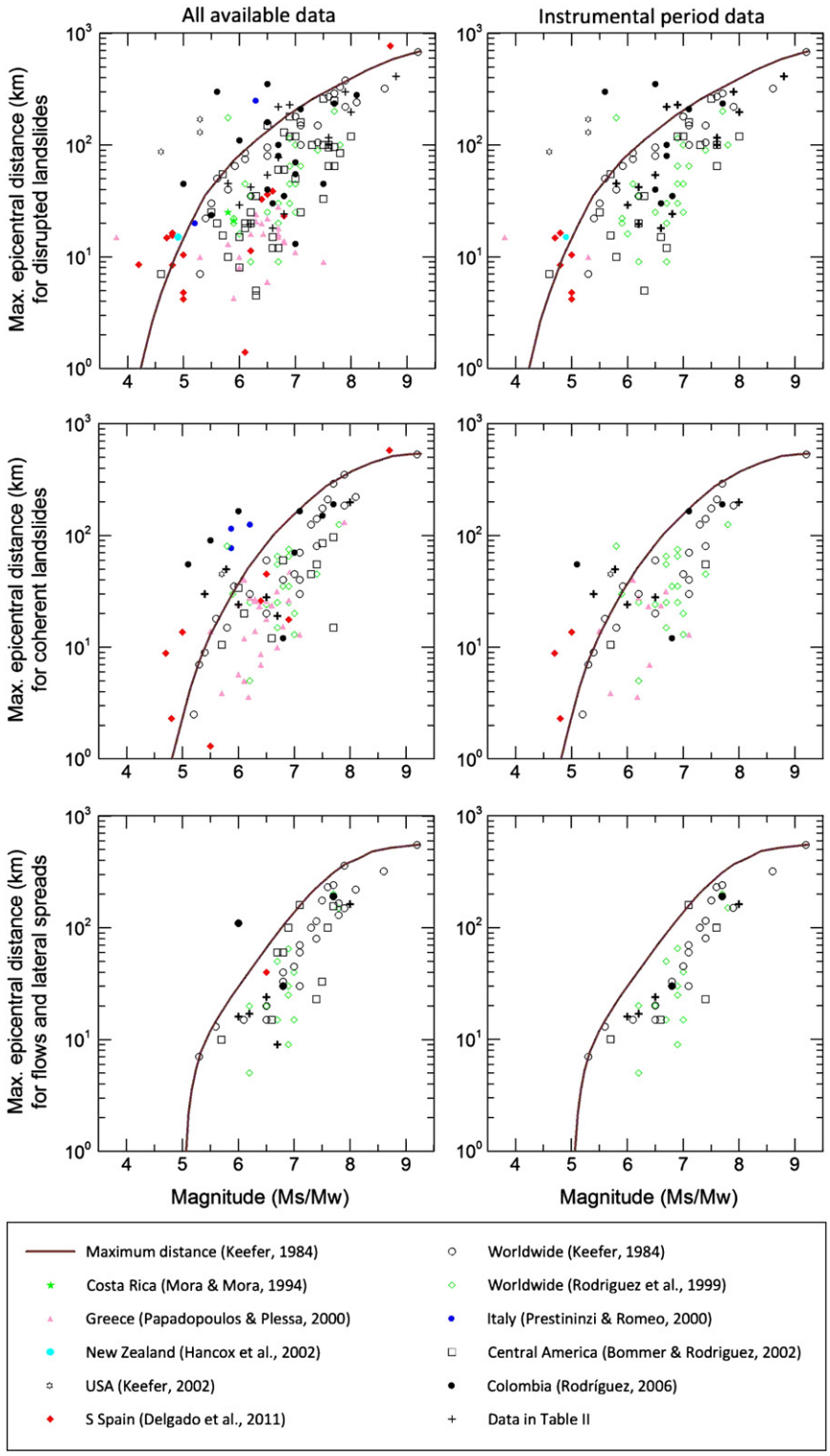

Fig. 2. Distribution of maximum distances for seismic induced landslides as a function of earthquake magnitude and landslide typology.

fault zone, or the western limit between the Eurasian and Africa plates, which is a linear shaped feature where shallow, high magnitude events occur. Because this is a historical event, some uncertainties arose about its location and magnitude, which may partially explain the very far distances observed. Additionally, due to the large magnitude of this event, the use of epicentral distance was probably not a good measure of landslide-source distance.

To avoid errors due to location or determination of the magnitude of the event, separate plots with all/instrumental period data were prepared, and many of the outliers still appeared in the instrumental period plot (right part of Figure 2).

Available data on the characteristics of outliers were compiled and analyzed. Note that there is only one example of such a landslide in the flow/lateral spread group, so this group was excluded in the following analysis. This analysis did not include data from landslides triggered by very low magnitude earthquakes ($M<3.0$) that were included in Table 1 or referred to by other authors (Keefer, 1984; Rodríguez et al., 1999).

For those cases where outliers were reported, we carefully checked the geological description of the natural materials in which the landslides were reported (which were not always available). Because such descriptions varied depending on the authors, data were grouped into broad, general categories following the simple classification employed by Bommer and Rodríguez (2002) and Rodríguez (2006). The geological context where outliers were described was simplified into five, broad, geological groups of materials: jointed rock, marly/clayey soils, alluvial/colluvial sediments, volcanic soils and residual soil slopes (Figure 3). Outliers in the disrupted landslides category comprise rock/soil falls and shallow disrupted soil slides. They are usually reported to occur in areas prone to landslides and equally affected (similar frequency) all geological groups, although they were more frequent in jointed rock slopes. Similarities in the frequency of occurrence of disrupted landslides, irrespective of the nature of slope, may indicate that they occurred because the slope was in a precarious state, close to the limit equilibrium, reflecting the natural susceptibility of slopes. Any slope in this condition might fail if an earthquake were to occur. This would explain why this type of landslide was the more frequently triggered by earthquakes and why they occur at farther distances (Keefer, 1984; Rodríguez et al., 1999).

It is noticeable that most coherent landslides occurred on fine, cohesive slopes of soils, although they were also described when rigid rock blocks rest on ductile, saturated materials (Lefebvre et al., 1992; Rodríguez et al., 1999; Rodríguez, 2006). These different patterns of occurrence may reflect differences in the mechanical behavior of materials that could favor (or prevent) this type of slope failure. Due to their granular texture, non cohesive soils easily disaggregate when they fail, forming disrupted landslides but not coherent masses. Large coherent slide outliers ($>10^6$ m^3) involving cohesive soils may occur in areas of smooth relief, with the rupture zone located several dozens of meters below the ground surface (Jiménez Pintor and Azor, 2006; Bozzano et al., 2008a,b, 2010). For these last examples, they seemed to be pre-existing landslides that reactivated during certain earthquakes. Site effects have been argued to explain the reactivation in all cases (Figure 4a).

Among the possible effects that can contribute to the occurrence of far field landslides, it is interesting to note that site effects have been mentioned as the probable cause for both disrupted and coherent landslides; they always affected cohesive soil slopes resting on a rigid substratum (Figure 4a). In one case (the 1988 Saguenay earthquake), simultaneous presence of susceptible, saturated materials (sensitive clays underlain by glacial till) and the focusing of seismic waves by the reflection of shear waves at the lower crust probably explain the far distances observed (Sommerville et al., 1990; Lefebvre et al., 1992). The contribution of rainy periods, during or immediately

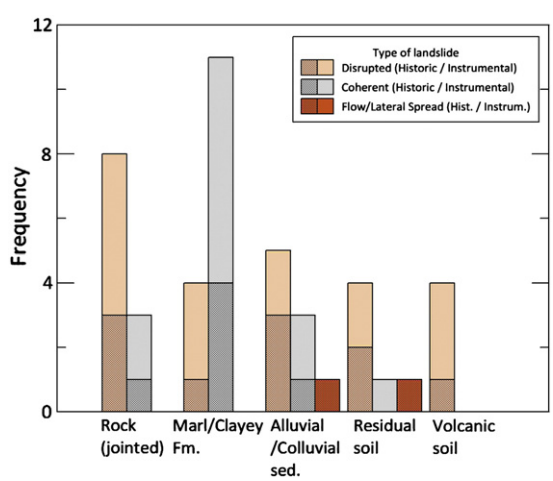

Fig. 3. Frequency of far field (outliers) seismic-induced landslides as a function of geological context/material of affected slopes.

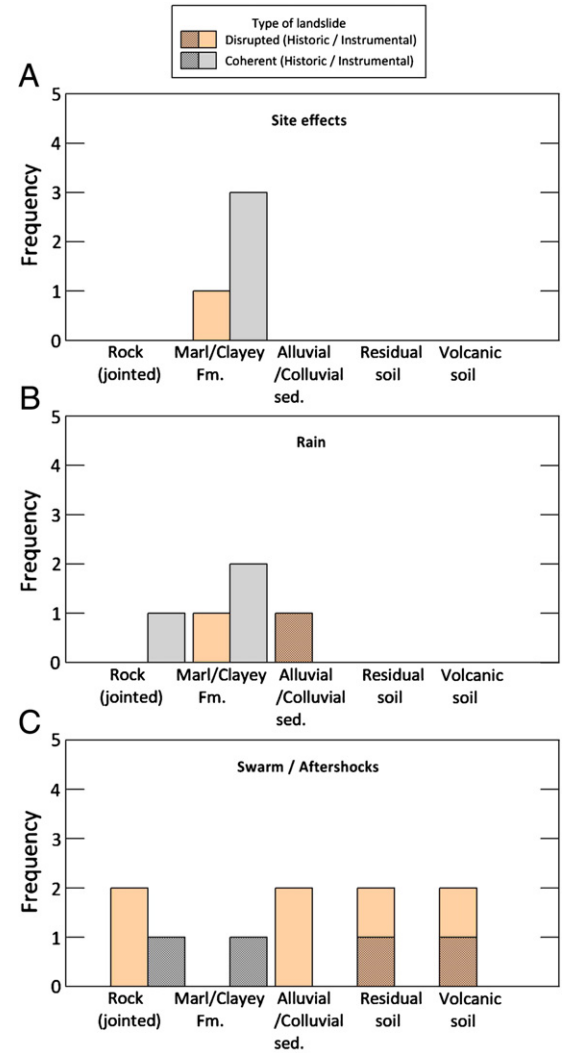

Fig. 4. Contribution of (a) site effects, (b) rain and (c) occurrence of seismic series in the occurrence of far field (outliers) seismic-induced landslides.

before the earthquake, to the occurrence of seismic-induced landslides is well documented (Mora and Mora, 1994). During shaking, pore-water pressure may increase, reducing the shear strength of slopes. Available data (Figure 4b) confirmed that it can also contribute to triggering far field landslides when earthquakes take place in rainy areas, and landslides may be of any typology and affect any type of the simplified geological groups of materials described above.

The occurrence of seismic series prepares the terrain, making it weaker and susceptible as the events of the series occur (Papadopoulos and Plessa, 2000; Rodríguez, 2006; Wick et al., 2010). In this sense, available data showed that this effect contributes to the triggering of far field disrupted landslides of rocky, granular or volcanic soil slopes. For slopes on cohesive materials, they were more likely to be coherent landslides (Figure 4c). There is no straightforward explanation for this pattern, although it would reflect either a change in the mechanical behavior of materials or the stress status of the slope involved.

Other differences can be identified between outliers of disrupted and coherent landslides in these figures. The main difference was that disrupted landslides could be induced by very low magnitude earthquakes. Such events create short-time, high frequency wavefields that can dislocate shallow, brittle materials. On the contrary, longer durations and low periods are usually needed to trigger larger, coherent landslides. An example of disrupted landslides induced by a very low magnitude earthquake was been found at the North Loja, 1991

earthquake, 45 km W of Granada (southern Spain; Table 1). Several small-sized rock falls (the largest block size was approximately 5 m^3) were induced by an earthquake of a magnitude (mbLg) as low as 2.6. The source area for the landslides was a natural slope located above a road cut on fractured limestone. There were two sets of discontinuities dipping towards the free face of the slope that formed wedges favoring the individualization and movement of the blocks. They fell down and bounced on the road, creating several craters and partially closing the road for two weeks. There were two witnesses, who alerted the local authorities and ensured the accuracy of the triggering time, which coincided with the occurrence of an earthquake in the same area reported by the National Seismic Network (IGN). No rain had been recorded for several weeks prior to the occurrence of the landslides, so the possibility of its contribution as a triggering factor can be discarded; a seismic origin is most likely. In this case, there were some economic losses (repair to the road and inconvenience caused by its closure) but fortunately, there were no casualties.

Another difference between the two types of outliers was that for equal magnitude, disrupted landslides, outliers may have occurred at farther distances than for coherent ones. This is logical because the energy cost, in terms of moving a coherent mass of soil or rock, is greater than that required for the detachment of small-sized, shallow soil masses or rock blocks previously separated from the slope mass, which are the most frequent types of seismically induced landslides (Keefer, 1984).

Perkins (1997) and Rodríguez et al. (1999) pointed out an interest in using macroseismic intensity for seismic hazard studies because the hazard increases with the severity of ground motion due to ground (site) effects, which is something that the magnitude of the event by itself cannot account for. For this reason, a plot of available maximum distance–epicentral intensity (Io) data for each earthquake, organized following the three categories proposed by Keefer (1984), is presented in Fig. 5. In a recent study, Musson et al. (2010) addressed the problem of conversions among macroseismic intensity

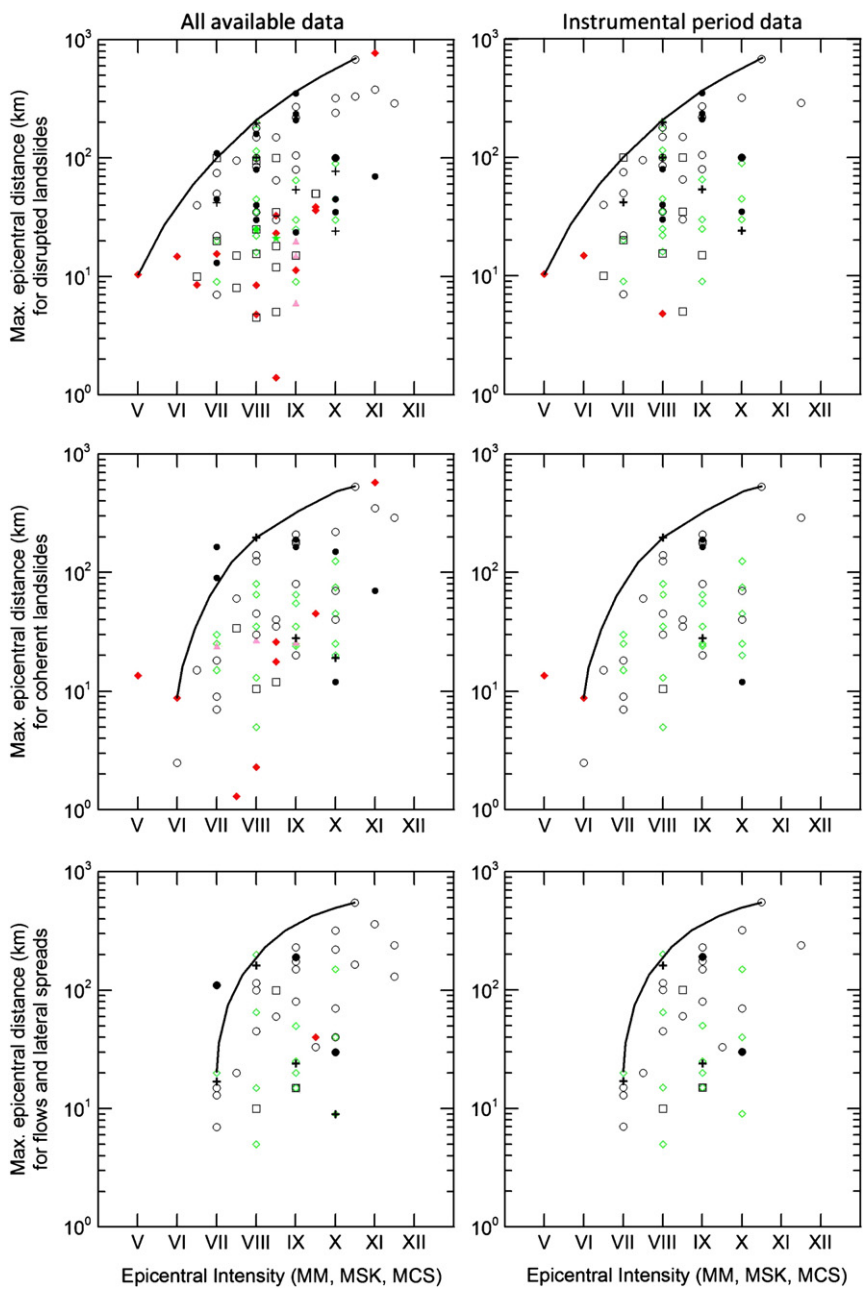

Fig. 5. Distribution of maximum distances for seismic induced landslides as a function of macroseismic intensity of events and landslide typology. See Fig. 2 for legend of symbols.

scales, and their conclusions pointed out that assignments made with the macroseismic scales derived from the same root (i.e., the Mercalli scale) do not differ consistently, and differences are of the same size as uncertainties related to the assignment procedure. Consequently, no conversion between intensities scales (i.e. MCS, MSK, MM…) has been done and the original intensity values have been retained, excluding only intensities evaluated with the EMS scale, that do not take into account the ground effects in its evaluation. Available data include 147 records with epicentral intensity assigned by different scales including 136 assigned by the MMI, MSK or MCS scales, and 11 by the EMS-98 scale only.

There are no worldwide upper bound distance curves that have made use of Io similar to that proposed by Keefer (1984), although regional based curves have been proposed for Italy (Prestininzi and Romeo, 2000) and southern Spain (Delgado et al., 2011). Therefore the instrumental data subset has been used to draw the curve that delimits the boundaries of the maximum distances for each degree of intensity. Then, the same curve was drawn in the plot containing all available data. It is interesting to note that although the whole database contains about 50% more data (probably with greater errors in the location of epicenter and, consequently, in the computation of distances to the induced landslides) the same curves bound the data well for both categories. There are only three exceptions: two of them correspond to historical events that occurred in Colombia (Rodríguez, 2006) and the third one is an active, extremely slow, rotational slide that accelerated its rate of movement during the 1984, Lentejí earthquake (southern Spain). Because this landslide already existed and was moving when the earthquake occurred, it was discarded from the definition of the limiting distance for this type of landslide.

With these curves, some distinctive patterns can be recognized for each landslide typology. The main difference is that disrupted landslides can occur at lower epicentral intensities (intensity V compared to VI and VII for coherent and flow/lateral spread types, respectively) and farther away (at equal epicentral intensity) than the other typologies. Note that if epicentral intensity should be at least V for inducing disrupted landslides, intensity at the sites of landslide occurrence may be even lower, as described by several authors (i.e., Keefer, 1984; Rodríguez et al., 1999). For low intensities, differences in maximum distances may be significant among typologies, but they tend to diminish (and basically disappear) for epicentral intensities of VIII to IX. It is interesting to note that although the macroseismic intensity is based on damage and has no direct translation in terms of radiated energy, patterns in the distribution of landslides were similar to that observed when magnitude is employed for similar purposes (Keefer, 1984; see also Figure 2).

Fig. 6 shows the available data on the area affected by landslides as a function of magnitude/epicentral intensity of the earthquakes. For the magnitude plots, upper bound curves proposed by Keefer (1984) and Rodríguez et al. (1999) were also plotted. As in the case of the maximum distances (Figure 2), several outliers occurred with respect to these upper bounds, although they may occur across practically the full range of magnitudes. Additionally, for outliers of lower magnitude ($M \leq 5$), areas are only slightly greater than those predicted by upper bound curves. A significant modification of the Rodríguez et al. (1999) curve would include these data. For events above this threshold, differences became very important. Most outlier data were from Colombia, in areas where alluvial and residual soils exist in combination with steep terrain and very high precipitation during rainy periods (Snow, 1976). In this sense, this area is characterized

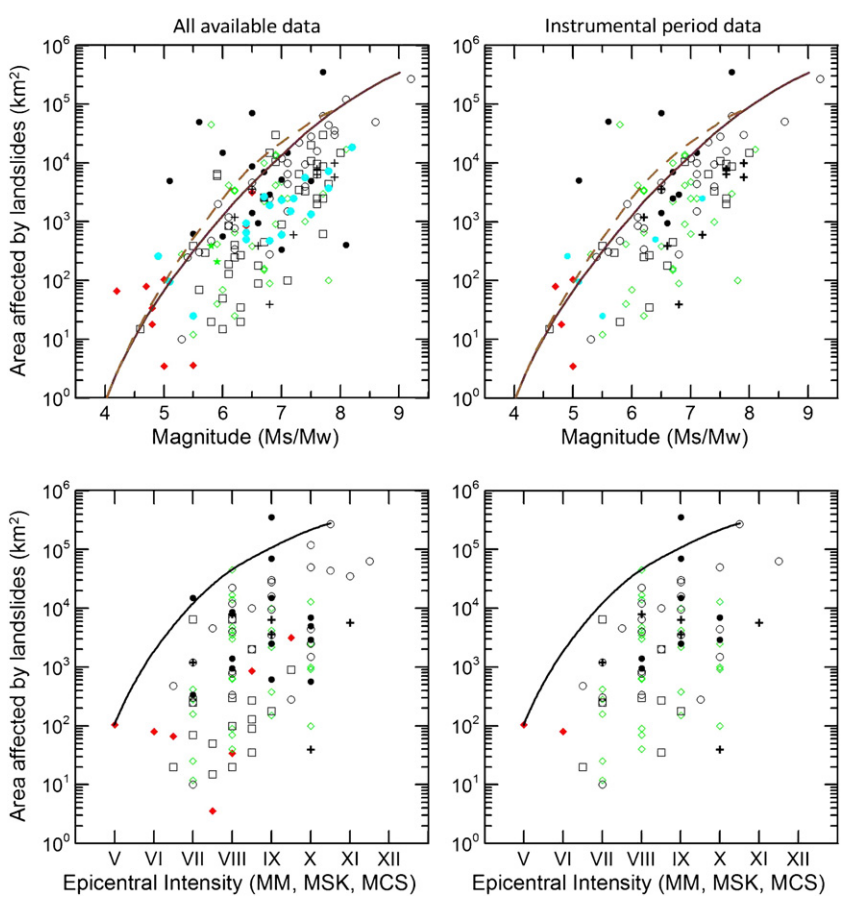

Fig. 6. Distribution of areas affected by landslides as a function of event magnitude (top) and macroseismic epicentral intensity (bottom). Solid line is maximum area proposed by Keefer (1984); dash line is the maximum area proposed by Rodríguez et al. (1999). See Fig. 2 for legend of symbols.

by meeting all conditioning factors previously discussed for distance outliers (Figure 4). Additionally, several of these data represent the area affected by landslides after the occurrence of seismic series (Rodríguez, 2006), which could explain the very large areas observed.

There is no available upper bound curve for areas affected by landslides that make use of Io. With the purpose of obtaining such a relationship, a procedure similar to that described for maximum distances against Io was followed. There were few data available in the low to moderate intensity range (Io<VII), and consequently the limiting curve might change when more data becomes available. The proposed curve was also plotted in Fig. 6. For Io = V–VI, landslides may affect areas of about 100 km^2, which is in agreement with data on maximum distances (Figure 5). For high Io values, areas approached hundreds of thousands of square kilometers. There was only one outlier for the proposed curve. It corresponded to the December 12, 1979, Tumaco (Colombia) earthquake. This was a shallow event that caused many landslides and liquefaction of sand fills and Holocene deposits (Herd et al., 1981). Data about the landslide area was taken some time after the main shock, and included the effect of the main event and the successive aftershocks; consequently, this should be treated as a multiple event (Rodríguez, 2006), which would explain the very large area affected.

5. Conclusions

Landslides can be triggered by earthquakes and may affect wide and distant areas, far from the epicenter. In the last two decades, much effort has been invested in studying this phenomenon, and several researchers have compiled worldwide, country or regional databases. In this study, such databases have been examined and linked, and the pattern of the distribution of landslides with respect to earthquake severity, expressed as magnitude and macroseismic intensity, was studied.

The maximum distance of seismically induced landslides from the epicenter increases with the severity of the earthquake, and the upper bound curves for such distances, as proposed by Keefer (1984), fit most of the available data well, although some outliers were identified for disrupted and coherent type landslides at moderate to low magnitudes. Several factors may explain such outliers. Among them, available data show that the susceptibility of slopes prior to earthquake occurrence may play a key role in the occurrence of far field landslides. This phenomenon was recognized in five broad groups of materials: (jointed) rock masses, marl and/or clayey soils, alluvial and colluvial sediments, volcanic soils and residual soil slopes. Susceptible slopes in these broad groups of materials were prone to facilitate far field landslides, although the frequency of each type of landslide was not the same for each geological group. Far field, disrupted landslides were equally frequent in all geological groups, but perhaps more so on rocky slopes. By contrast, far field induced coherent landslides were more frequent on marly/clayey slopes.

Factors other than the susceptibility of slopes themselves may also contribute to triggering far field landslides. Among them, antecedent rain (allowing the generation of high pore-water pressures during shaking), site effects (that increase ground motion severity), or the occurrence of seismic swarms/series were most frequently cited by authors. Available data show that rain may be very effective in contributing to triggering far field landslides of any typology. By contrast, site effects were cited to be important on slopes of marls/clays lying on a rigid substratum or on already sheared slopes, hosting preexisting landslide masses responsible for a significant impedance contrast with the more rigid substratum. The occurrence of seismic series may also contribute, triggering disrupted landslides on granular soil slopes and coherent landslides in rocky/cohesive soils.

From the database compiled, it was also observed that for events of equal magnitude, disrupted landslide type outliers may occur further away than those of the coherent landslide type.

The same database was used to determine upper bound curves for landslide occurrence as a function of macroseismic intensity of events. The resulting curves showed very similar maximum distances for disrupted and coherent types of landslides of high intensity (VIII to X), while disrupted landslides may occur at farther distances than coherent or lateral spread/flows at higher intensities. In the low intensity range, disrupted landslides may be triggered by events of epicentral intensity as low as V, while the remaining types were only documented for intensities above VI.

When the analysis focused on the area affected by landslides, several outliers emerged with respect to previously proposed limiting distances. For some of them, the differences were small. Because they occur in the low magnitude range, where few data were available when the curves were proposed, such curves could be modified to include these low magnitude data. Other outliers occur at moderate and high magnitudes. In these cases, many data were obtained from seismic series, which might increase the area affected and explain such large areas. Similar to maximum distances, a new curve for defining maximum area affected by landslides as a function of macroseismic intensity was proposed.

Acknowledgments

This work has been partially supported by the project DGI-MEC CGL2007-60535/BTE and the research groups RNM-370 (Junta de Andalucía) and VIGROB-184 (Universidad de Alicante). The authors wish to thank R. Romeo (Univ. Urbino, Italy) for providing the original database of the CEDIT catalog, and F.J. García-Tortosa (Univ. Jaén, Spain) and P. Alfaro (Univ. Alicante, Spain) for providing data from recent events in SE Spain. The study is also part of the research activities in the frame of the bilateral agreement between the Department of Earth Science of the University of Rome "Sapienza" and the Department of Earth Science of the University of Alicante. The suggestions of two anonymous reviewers greatly improved the original manuscript.

References

Ashford, S.A., Sitar, N., 1997. Analysis of topographic amplification of inclined shear waves in a steep coastal bluff. Bulletin of the Seismological Society of America 87, 692–700.

Basili, R., Valensise, G., Vannoli, P., Burrato, P., Fracasi, U., Mariano, S., Tiberti, M.M., Boschi, E., 2008. The database of individual seismogenic sources (DISS), version 3: summarizing 20 years of research on Italy's earthquake geology. Tectonophysics 453, 20–43http://legacy.ingv.it/DISS/ (On-line web site).

Blumetti, A.M., Comerci, V., Di Manna, P., Guerrieri, L., Vittori, E., 2009. Geological effects induced by the L'Aquila earthquake (6 April 2009, Ml 5.8) on the natural environment. Preliminary report. Dipartimento Difesa del Suolo Servizio geologico d'Italiahttp://www.apat.gov.it/site/_files/Inqua/2009_abruzzo_earthquake_report.pdf (Available on web-site).

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

Bouchon, M., 1973. Effect of topography on surface motion. Bulletin of the Seismological Society of America 63, 615–632.

Bouchon, M., Schultz, C.A., Toksoz, M.N., 1996. Effect of three dimensional topography on seismic motion. Journal of Geophysical Research 101, 835–846.

Bouckovalas, G.D., Papadimitriou, A.G., 2005. Numerical evaluation of slope topography effects on seismic ground motion. Soil Dynamics and Earthquake Engineering 25, 547–558.

Bouhadad, Y., Nour, A., Slimani, A., Laouami, N., Belhai, D., 2004. The Boumerdes (algeria) earthquake of May 21, 2003 (Mw = 6.8): ground deformation and intensity. Journal of Seismology 8, 497–506.

Bouhadad, Y., Benhamouche, A., Maouche, S., Belhai, D., 2009. Evidence for Quaternary liquefaction-induced features in the epicentral area of the 21 May 2003 Zemmouri earthquake (Algeria, Mw = 6.8). Journal of Seismology 1, 161–172.

Bozzano, F., Gambino, P., Larosa, I., Scarascia Mugnozza, G., 2001. Analisi preliminare degli effeti di superficie indotti dalla sequenza sísmica umbro-marchigiana nei mesi dei settembre-ottobre 1997. Memorie della Società Geoligica Italiana 56, 283–290.

Bozzano, F., Lenti, L., Martino, S., Paciello, A., Scarascia Mugnozza, G., 2008a. Self-excitation process due to local amplification responsible for the reactivation of the Salcito landslide (Italy) on 31 October 2002. Journal of Geophysical Research 113, B10312. doi:10.1029/2007JB005309.

Bozzano, F., Cardarelli, E., Cercato, M., Lenti, L., Martino, S., Paciello, A., Scarascia Mugnozza, G., 2008b. Engineering–geology model of the seismically induced Cerda landslide. Bollettino di Geofisica Teorica e Applicata 49, 205–226.

Bozzano, F., Lenti, L., Martino, S., Paciello, A., Scarascia Mugnozza, G., 2010. Evidences of landslide earthquake triggering due to self-excitation process. International Journal of Earth Sciences. doi:10.1007/s00531-010-0514-5 (online first from February 2010).
CEREIS, Centro Regional de Sismología para América del Sur, 2010. Catálogo de intensidades. www.cereis.org/portal/catal_inten.php2010.
Del Gaudio, V., Wasowski, J., 2010. Advances and problems in understanding the seismic response of potentially unstable slopes. Engineering Geology. doi:10.1016/j.enggeo.2010.09.007 (online first from August 2010).
Delgado, J., Peláez, J.A., Tomás, R., García-Tortosa, F.J., Alfaro, P., López Casado, C., 2011. Seismically-induced landslides in the Betic Cordillera (S Spain). Soil Dynamics and Earthquake Engineering 31, 1203–1211.
Duncan, J.M., Wright, S.G., 2005. Soil strength and slope stability. J. Willey & Sons, Hoboken (N.J.), p. 312.
EMERGEO, Working Group, 2009. Evidence for surface rupture associated with the Mw 6.3 L'Aquila earthquake sequence of April 2009 (central Italy). Terra Nova 22, 43–51. doi:10.1111/j.1365-3121.2009.00915.x.
Esposito, E., Porfido, S., Simonelli, A.L., Mastrolorenzo, G., Iaccarino, G., 2000. Landslides and other surface effects induced by the 1997 Umbria-Marche seismic sequence. Engineering Geology 58, 353–376.
Esposito, E., Pece, R., Porfido, S., Tranfaglia, G., 2009. Ground effects and hydrological changes in the Southern Apennines (Italy) in response to the 23 July 1930 earthquake (Ms = 6.7). Natural Hazards and Earth System Sciences 9, 539–550.
Garrido, J. (1991). Informe sobre la conservación de carreteras en la provincia de Granada. Delegación Provincial de Carreteras, Consejería de Obras Públicas y Transportes. Junta de Andalucía. Internal Report.
Geli, L., Bard, P.Y., Jullien, B., 1988. The effect of topography on earthquake ground motion: a review and new results. Bulletin of the Seismological Society of America 78, 42–63.
GNDT, Gruppo Nazionale per la Difesa dai Terremoti, 1996. NT4.1: un catalogo parametrico di terremoto di area italiana al di sopra della soglia del danno, compilato da R. Camassi e M. Stucchi, CNR-GNDT, Milano, noviembre 1996. http://emidius.itim.mi.cnr.it/NT.html 1996 (On-line web).
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.
Harbi, A., Maouche, S., Ousadou, F., Rouchiche, Y., Yelles-Chaouche, A., Merahi, M., Heddar, A., Nouar, O., Kherroubi, A., Beldjoudi, H., Ayadi, A., Benouar, D., 2007. Macroseismic study of the Zemmouri earthquake of 21 May 2003 (Mw 6.8, Algeria). Earthquake Spectra 23, 315–332.
Harp, E.L., Noble, M.A., 1993. An engineering rock classification to evaluate seismic rock-fall susceptibility and its implication to the Wasatch Front. Bulletin of the Association of Engineering Geologists 30, 293–319.
Havenith, H.B., Vanini, M., Jongmans, D., Faccioli, E., 2003. Initiation of earthquake-induced slope failure: influence of topographical and other site effects. Journal of Seismology 7, 397–412.
Herd, D.G., Youd, T.L., Meyer, H., Arango, J.L., Person, W.J., Mendoza, C., 1981. The great Tumaco, Colombia earthquake of 12 December 1979. Science 211 (4481), 441–445.
Hoek, E., Bray, J.W., 1981. Rock slope engineering, Revised third edition. Institution of Mining and Metallurgy, Taylor and Francis, London, p. 358.
Hutchinson, J.N., 1988. General Report: Morphological and geotechnical parameters of landslides in relation to Geology and Hydrogeology. In: Bonnard, C. (Ed.), Proceedings of the Fifth International Symposium on Landslides, Vol. 1. Balkema, Rotterdam, pp. 3–35.
INGEMMET, 2007. Informe Conjunto: Movimientos en masas y deformaciones superficiales asociados al sismo de Pisco, 2007. Informe Técnico. Ministerio de Energía y Minas, p. 172.
INGV, 2004. Database Macrosismico Italiano 2004. http://emidius.mi.ingv.it/DBMI04/ 2004.
Iverson, R.M., 2000. Landslide triggering by rain infiltration. Water Resources Research 36 (7), 1897–1910.
Jibson, R.W., Harp, E.L., Schulz, W., Keefer, D.K., 2006. Large rock avalanches triggered by the M 7.9 Denali fault, Alaska, earthquake of 3 November 2002. Engineering Geology 83, 144–160.
Jiménez Pintor, J., Azor, A., 2006. El deslizamiento de Güevéjar: estudio de una inestabilidad desencadenada por terremotos. Geogaceta 40, 287–290.
Kazhai, B., Sitar, N., 2003. Evaluation of factors controlling earthquake-induced landslides caused by Chi-Chi earthquake and comparison with the Northridge and Loma Prieta events. Engineering Geology 71, 79–95.
Keefer, D.K., 1984. Landslides caused by earthquakes. Geological Society of America Bulletin 95, 406–421.
Keefer, D.K., 2000. Statistical analysis of an earthquake-induced distribution — the 1989 Loma Prieta, California event. Engineering Geology 58, 213–249.
Keefer, D.K., 2002. Investigating landslides caused by earthquakes — a historical review. Surveys in Geophysics 23, 473–510.
Keefer, D.K., Wartman, J., Navarro Ochoa, C., Rodríguez-Marek, A., Wieczorek, G.F., 2006. Landslides caused by the M 7.6 Tecomán, Mexico earthquake of January 21, 2003. Engineering Geology 86, 183–197.
Lefebvre, G., Leboeuf, D., Hornych, P., 1992. Slope failures associated with the Saguenay earthquake, Quebec, Canada. Canadian Geotechnical Journal 29, 117–130.
Lenti, L., Martino, S., 2010. The LEMA_DES approach for deriving dynamic equivalent signals: numerical modeling of input-slope interaction. Proc. 14ECEE Ohrid (Macedonia), pp. 1–9.
Liao, H.W., Lee, C.T., 2000. Landslides triggered by the Chi-Chi earthquake. Proceedings of the 21th Asian Conference on Remote Sensing, Taipei, Taiwan, pp. 383–388.
Mahdavifar, M.R., Solaymani, S., Jafari, M.K., 2006. Landslides triggered by the Avaj, Iran earthquake of June 22, 2002. Engineering Geology 86, 166–182.
Martínez Solares, J.M., 2001. Los efectos en España del terremoto de Lisboa (1 de noviembre de 1755). Ministerio de Fomento. Monografía núm, 19. Dirección General del Instituto Geográfico Nacional, p. 756.
Martínez Solares, J.M., López Arroyo, A., 2004. The great historical 1755 earthquake. Effects and damage in Spain. Journal of Seismology 8, 275–294.
Meunier, P., Hovius, N., Haines, J.A., 2008. Topographic site effects and the location of earthquake induced landslides. Earth and Planetary Science Letters 275, 221–232.
Miccadei, E., Piacentini, T., Sciarra, N., 2010. Landslides seismically induced during the earthquake of 6th April 2009 in Abruzzo region (Central Italy). In: Williams, A.L., Pinchers, G.M., Chin, C.Y., McMorran, T.J., Massey, C.I. (Eds.), Geologically Active. Proc. 11th IAEG Congress, Aukland, New Zeland 5–10 Sept 2010. Taylor&Francis group, London. ISBN: 978-0-415-60034-7, pp. 127–141.
Mora, S., Mora, R., 1994. Los deslizamientos causados por el terremoto de Limón: Factores de control y comparación con otros eventos en Costa Rica. Revista Geologica de America Central 139–152 (Vol. esp. Terremoto de Limón).
Musson, R.N.M., Grünthal, G., Stucchi, M., 2010. The comparison of macroseismic intensity scales. Journal of Seismology 14, 413–428.
Nguyen, K.V., Gatmiri, B., 2007. Evaluation of seismic ground motion induced by topographic irregularity. Soil Dynamics and Earthquake Engineering 27, 183–188.
Papadimitriou, A.G., Chaloulos, Y., 2010. Aggravation of the peak seismic acceleration in the vicinity of 2D hills, canyons and slopes. Proc. Fifth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics (S. Diego – California, 24-29/05/2010). Paper n°3-26a, pp. 1–12.
Papadopoulos, G.A., Plessa, A., 2000. Magnitude-distance relations for earthquake–induced landslides in Greece. Engineering Geology 58, 377–386.
Papathanassiou, G., Pavlides, S., Ganas, A., 2005. The 2003 Lefkada earthquake: field observations and preliminary microzonation map based on liquefaction potential index for the town of Lefkada. Engineering Geology 82, 12–31.
Parise, M., Jibson, R.W., 2000. A seismic landslide susceptibility rating of geologic units based on analysis of characteristics of landslides triggered by the 17 January, 1994 Northridge, California earthquake. Engineering Geology 58, 377–386.
Perkins, D.M., 1997. Landslide hazard maps analogues to probabilistic earthquake ground hazard maps. In: Cruden, D., Fell, R. (Eds.), Landslide risk assessment. Balkema, Rotterdam, pp. 327–332.
Porfido, S., Esposito, E., Guerrieri, L., Vittori, E., Tranfaglia, G., Pece, R., 2007. Seismically induced ground effects of the 1805, 1930 and 1980 earthquakes in the Southern Apennines, Italy. Bollettino. Societa Geologica Italiana (Italian Journal of Geoscience) 126, 333–346.
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.
Rogozhin, E.A., Ovsyuchenko, A.N., Marakhanov, A.V., Novikov, S.S., 2009. Tectonic position and geological manifestations of the 2006 Olyutor earthquake in Koryakia. Geotectonics 43, 443–461.
Romeo, R., Delfino, L., 1997. CEDIT – Catalogo nazionale degli effetti deformativi del suolo indotti da forti terremoti. Servizio Sismico Nazionale. Technical Report SSN/RT/97/04, p. 41 http://www.dstn.pcm.it/ssn/index.html (Originally in the web site).
Sato, H.P., Harp, E.L., 2009. Interpretation of earthquake-induced landslides triggered by the 12 May 20008, M7.9 Wenchuan earthquake in the Beichuan area, Sichuan province, China using satellite imageri and Google Earth. Landslides 6, 153–159.
Sepúlveda, S.A., Serey, A., Lara, M., Pavez, A., Rebolledo, S., 2010. Landslides induced by the April 2007 Aysén Fjord earthquake, Chilean Patagonia. Landslides 7, 483–492.
Snow, J.W., 1976. The climate of Northern South America. In: Landsberg, H.E. (Ed.), World survey of climatology, vol. 12. Elsevier, Amsterdam (Chapter 6).
Sommerville, P.G., McLaren, J.P., Saikia, C.K., Helmberger, D.V., 1990. The 25 November 1988 Saguenay, Quebec, earthquake: source parameters and the attenuation of strong motion. Bulletin of the Seismological Society of America 80, 1118–1143.
USGS, 2009. Magnitude 8.0 – Near the coast of Central Perú. http://earthquake.usgs.gov/eqcenter/eqinthenews/2007/us2007gbcv/2009.
Wang, H.B., Sassa, K., Xu, W.Y., 2007. Analysis of a spatial distribution of landslides triggered by the 2004 Chuetsu earthquakes of Niigata Prefecture, Japan. Natural Hazards 41, 43–60.
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.
Wieczoreck, G.F., 1996. Landslide triggering mechanisms. In: Turner, A.K., Schuster, R.L. (Eds.), Landslides, investigation and mitigation. Special Report 247. TRB National Research Council. National Academy Press, Washington D.C, pp. 76–90.
Yagi, H., Sato, G., Higaki, D., Yamamoto, M., Yamasaki, T., 2009. Distribution and characteristics of landslides induced by the Iwate-Miyagi Nairiku earthquake in 2008 in Tohoku district, Northeast Japan. Landslides 6, 335–344.
Záruba, Q., Mencl, V., 1982. Landslides and their control, Second completely revised edition. Developments in Geotechnical Engineering, 31. Elsevier, Amsterdam, p. 324.