Landslides Triggered by Earthquakes from 1920 to 2015

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Abstract

Seismic activity is one of the major causes of landslides around the world. Several studies have examined the characteristics of earthquake-induced landslides following major earthquake events. Previous studies have also combined the characteristics of the earthquakes and the landslides triggered from these studies to develop relationships between the magnitude of the earthquake and the total area affected by the earthquake, the maximum distance to the landslide observations from the epicenter or fault rupture. However, the relationships between the magnitude and the number of landslides as well as the peak ground acceleration and the number of landslides have not been developed. In this study, 35 historical earthquake events from 1920 to 2015 were examined. The results show that the previous proposed relationship between the magnitude of the earthquake and the total area affected by the landslides is valid for the earthquake events examined in this study. However, in this paper a relationship between the peak ground acceleration and the total area affected by landslides is developed. In addition, the total number of moderate to large scale landslides and total number of all landslides have been correlated with the magnitude and the peak ground acceleration. The results from this study suggest the use of the peak ground acceleration as opposed to the earthquake magnitude in the study of earthquake-induced landslides.

Keywords

Earthquake-induced landslides • PGA • Seismic hazards • Historical database

Introduction

One of the major causes of landslides is seismic activity and as a result, earthquake-induced landslides have been the focus of many studies that have turned to small and large scale physical modelling, numerical analyses, or examining the characteristics of landslides induced during recent earthquakes to better understand the factors triggering and consequences of these landslides. Keefer (1984) complied data from 40 historical earthquakes occurring between 1811 and 1980. Using this information, relationships between the magnitude of the earthquake, distance from the epicenter, and the total area affected by the landslides were derived. Rodriguez et al. (1999) expanded upon the database developed by Keefer (1984) to include an additional 36 earthquakes from 1980 to 1994 and found slightly different correlations between the earthquake magnitude and the total landslide area.

The work by Keefer (1984) and Rodriguez et al. (1999) made several important contributions to the understanding of the characteristics of earthquake-induced landslides. However, the most notable is probably the relationships between

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the seismic ground shaking in terms of the magnitude of the earthquake to the number of landslides and the area affected by the landslides and between the magnitude and the maximum distance of landslide observations from the epicenter in different geological, topographical, and climatic conditions. In both studies, the peak ground acceleration, which is a better indicator of the intensity of shaking, was not incorporated. This study adopts an approach similar to that in Keefer (1984) and Rodriguez et al. (1999) to understand how the peak ground acceleration affects the number of observed landslides in the areas within diverse geological, topographical, and climatic conditions. In addition, the study examines the relationship between the total number of landslides with the peak ground acceleration and magnitude of the earthquake.

Database and Its Characteristics

For this study, the database of earthquake-induced landslides was compiled from articles published in geotechnical and seismological journals, conferences, and reports. A total of 35 earthquakes from 1920 to 2015 were identified. Although the list of identified earthquakes and the resulting landslides is not comprehensive, it is believed that it encompasses all of the most important events that have some available documentation.

Earthquake Characteristics

Table 1 summarizes the characteristics of the earthquake events identified and used in this study. Specifically, Table 1 contains the names and dates of each of the earthquake events, the moment magnitude (when available) or the Richter surface-wave magnitude, the maximum peak ground acceleration, maximum Modified Mercalli Intensity (Medvedev 1962) and the focal depth. In addition, Table 1 also includes the number of observed landslides, the area of the region affected by these landslides, and the corresponding references for additional information. The 35 earthquake events examined in this study occurred between 1920 and 2015 and had magnitudes ranging from 5.1 to 9.0. The peak ground accelerations of the events ranged from 0.18 to 2.4g.

Landslide Characteristics

Landslides may be grouped into categories, as defined by Varnes (1987). A summary of these categories as well as the characteristics of the landslides observed in these categories is provided in Table 2. In the earthquake database used in this study, there were no subaqueous landslides and thus, this category has been removed from the rest of the discussions. The total number of observed landslides and the total area affected by these landslides was provided in Table 1. The information presented in the references cited in Table 1 for each earthquake does not allow for an accurate determination of the number of landslides in each category. However, based on the information provided (written descriptions, photographs, or field descriptions), the types of landslides triggered by each earthquake event could be determined and may be found as summarized in Table 3. Using the information in Table 3, the number of earthquake events in which each type of landslide that was observed was determined. The results are summarized in Fig. 1, which shows that the most common types of landslides in the historical database include rock falls, disrupted soil slides, and rock slides. Similarly, the least common types of landslides are soil falls, slow earth flows, soil lateral spreads and rapid soil flows. These results are similar to those obtained in Keefer (1984) and Rodriguez et al. (1999).

Characteristics of Earthquake-Induced Landslides

In both Keefer (1984) and Rodriguez et al. (1999), the characteristics of the earthquake-induced landslides as summarized by five relationships that were made in terms of the magnitude of the earthquake triggering the ground motion. However, the articles in the literature appear to suggest a stronger dependence of the triggering of earthquake-induced landslides on the peak ground acceleration. Thus, in this study, both the magnitude of the earthquake and the maximum peak ground accelerations experienced in the study area are related to the total number of observed landslides and the area affected by these landslides. It is noted that Keefer (1984) and Rodriguez et al. (1999) also examined the relationship between the maximum distance of the landslides from the epicenter and the maximum distance of triggered landslides from the fault rupture surface. Both of these are beyond the scope of this study and thus, are not included in this paper.

Smallest Seismic Parameters Triggering Landslides

Keefer (1984) and Rodriguez et al. (1999) both, first, identified the smallest magnitude of earthquake that triggered landslides in order to determine the lower bounds. The determination of these lower bounds was also completed in this study using both the magnitude of the earthquake and the maximum peak ground accelerations induced by each earthquake. The results are summarized in Table 4, which distinguishes the corresponding values of the magnitude and

Table 1 Characteristics of the earthquake events as well as the number of observed landslides and area affected by landslides triggered by these earthquakes

No.	Earthquake	Date		Mag.	Max. PGA (g)	Max. MMI	Focal depth (km)	No. of landslides	Area (km^2)	References
		Day	Year							
1	Haiyun	Dec. 16	1920	7.8	N/A	XII	N/A	39	N/A	Zhang and Wang (2007)
2	Daly City	Mar. 27	1957	5.3	0.18	VII	15	23	10	Bonilla (1960), Keefer (2002)
3	Peru	May 31	1970	7.9	0.60	VIII	45	1000	8300	Plafker et al. (1971), Harp et al. (2011)
4	San Fernando	Feb. 9	1971	6.7	1.25	XI	13	6000	3400	Morton (1971), Morton (1975), Harp et al. (2011)
5	Guatemala	Feb. 4	1976	7.5	0.60	IX	5	1000	16,000	Harp et al. (1981), Keefer (2002)
6	Mammoth Lakes	May 25	1980	6.2	0.24	VII	6	5170*	1220	Harp et al. (1984), Keefer and Wilson (1989), Wieczorek and Jäger (1996), Keefer (2002)
7	Mt. Diablo	Jan. 24	1980	5.8	0.56	X	5.9	103*	500	Wilson et al. (1985), Keefer and Wilson (1989), Keefer (2002)
8	Caolinga	May 2	1983	6.5	0.54	VIII	10	9389*	650	Keefer and Wilson (1989), Harp and Keefer (1990), Keefer (2002)
9	San Salvador	Oct. 10	1986	5.7	0.44	IX	10	216	N/A	Rymer (1987), Rymer and White (1989), Keefer (2002)
10	Loma Prieta	Oct. 17	1989	6.9	0.65	IX	19	1280	15,000	Keefer (2000)
11	Loma Prieta	Oct. 17	1989	6.9	0.65	IX	19	1500	2000	Keefer and Mason (1998), Keefer (2002)
12	Northridge	Jan. 17	1994	6.7	1.80	IX	18	11,300	10,000	Harp and Jibson (1996)
13	Hyogoken-Nanbu	Jan. 17	1995	6.9	0.83	XI	18	674	700	Fukuoka et al. (1997)
14	Hyogoken-Nanbu	Jan. 17	1995	6.9	0.83	XI	18	747	700	Sassa et al. (1995), Okimura and Torii (1999), Keefer (2002)
15	Umbria-Marche	Sept. 26	1997	6.1	0.36	VIII	10	200	N/A	Marzorati et al. (2002)
16	Umbria-Marche	Sept. 26	1997	6.1	0.36	VIII	10	112	700	Bozzano et al. (1998), Esposito et al. (2000), Keefer (2002)
17	Chi-Chi	Sept. 21	1999	7.7	0.50	X	7	10,000*	2400	Wang et al. (2003)
18	Chi-Chi	Sept. 21	1999	7.7	0.50	X	7	9272*	625	Liao and Lee (2000), Liao et al. (2002), Sitar and Bardet (2001), Uzarski et al. (2001)
19	Chi-Chi	Sept. 21	1999	7.7	1.00	X	7	1000	3750	Wang et al. (2002)
20	Avaj	June 22	2002	6.5	0.50	IX	10	500	3600	Mahdavifar et al. (2006)
21	Mid-Niigata	Oct. 23	2004	6.8	1.70	IX	13	1535*	N/A	Sato et al. (2005), Chigira and Yagi (2006)

(continued)

Table 1 (continued)

No.	Earthquake	Date		Mag.	Max. PGA (g)	Max. MMI	Focal depth (km)	No. of landslides	Area (km^2)	References
		Day	Year							
22	Mid-Niigata	Oct. 23	2004	6.8	1.80	IX	13	4400	N/A	Yamagishi and Iwahashi (2007)
23	Kashmir	Oct. 8	2005	7.6	0.80	VIII	26	2252	2550	Kamp et al. (2008)
24	Northern Pakistan	Oct. 8	2005	7.6	0.80	VIII	26	2424	2805	Sato et al. (2007)
25	Niigata Chuestu-Oki	July 16	2007	6.6	0.90	IX	10	70*	181	Collins et al. (2012)
26	Pisco	Aug. 15	2007	8.0	0.49	VI	39	134	27,000	Lacroix et al. (2013)
27	Iwate—Miyagi Nairku	June 14	2008	7.2	2.40	IX	10	4161*	600	Yagi et al. (2009)
28	Wenchuan	May 12	2008	7.9	0.63	XI	19	13,085*	31,686	Qi et al. (2010)
29	Wenchuan	May 12	2008	7.9	0.63	XI	19	60,104*	38,540	Gorum et al. (2011)
30	Port-au-Prince	Jan. 12	2010	7.0	0.50	X	13	30,828*	3192	Xu et al. (2012b)
31	Yushu	Apr. 14	2010	6.9	0.38	VIII	10	2036	1455	Xu et al. (2012a)
32	Lorca (SE Spain)	May 11	2011	5.1	0.36	VII	1	250	1000	Alfaro et al. (2012)
33	Tohoku	Mar. 11	2011	9.0	1.20	IX	29	3477	28,380	Wartman et al. (2013)
34	Gorkha (Main shock)	Apr. 25	2015	6.5	0.74	IX	19	3147	26,000	Tiwari et al. (2017)
35	Gorkha (Aftershock)	May 12	2015	6.8	0.8	IX	19	343	26,000	Tiwari et al. (2017)

*The numbers of landslides provided in this table are typically larger than 100 m^2 in area. However, a few studies, as indicated by the asterisk in the table, included smaller events yielding significantly larger landslide counts

the peak ground acceleration (PGA) for each type of landslide. It is clear from Table 4 that except for soil lateral spreads, a minimum magnitude of approximately 5 was necessary to trigger any of the other types of landslides. However, the lower bound for the maximum peak ground acceleration to trigger each type of landslide suggests more variability in the results. Specifically, it is clear that larger peak ground accelerations were required to trigger rock slides, soil falls, and disrupted soil slides even though it appears that these types of landslides have the same lower bound for the earthquake magnitude. Soil lateral spreads tended to have higher lower bound values for both the magnitude and the maximum peak ground acceleration in comparison to the other types of landslides.

The results presented should not suggest that the different types of landslides may not be observed at earthquake magnitudes or maximum peak ground accelerations lower than those listed in Table 4. This is entirely possible as a landslide may occur on a slope that is close to instability. Specifically, a particular slope may be stable under static conditions, but very weak shaking from a small magnitude earthquake or low peak ground accelerations may be sufficient to cause failure. As an example consider the failure of a cliff in Qinghai, China after a magnitude 2.9 earthquake in 1984 (Feng and Guo 1985). As pointed out by a number of researchers including Tiwari et al. (2017), Wartman et al. (2013), Khazai and Sitar (2004), Gorum et al. (2011), Bommer and Rodriguez (2002), Tiwari et al. (2016), among others, there are a number of factors asides from the magnitude and peak ground acceleration that will contribute to the occurrence of earthquake-induced landslides. However, these factors are ignored in determining the lower bounds for both the magnitude and the peak ground accelerations summarized in Table 4.

Area Affected by Earthquake-Induced Landslides

Shown in Fig. 2 is the relationship between the total area affected by the earthquake-induced landslides and the magnitude of the earthquake. The original upper bound relationship proposed by Keefer (1984) along with the proposed revision to this upper bound by Rodriguez et al. (1999) have both been included in Fig. 2 for comparison, as the solid black line and the dashed red line, respectively. From the figure, the revised relationship proposed by Rodriguez et al. (1999) agrees well with the observations for the total area affected by the landslides. There is one point that appears to be an outlier in terms of the revised relationship proposed by Rodriguez et al. (1999).

Table 2 Descriptions of landslide categories adapted from Varnes (1987) and Keefer (1984)

Category	Description
Rock falls Soil falls	Numerous small blocks and individual soil grains and rock fragments to material that is completely disaggregated into small rock fragments; material bounding, rolling, or free falling downslope; velocities are typically greater than 3 m/s; material can range from the dry to saturated conditions; typically less than 3 m in depth
Rock slides	Numerous small block and individual soil grains and rock fragments; involves translatational sliding on a shear plane; velocities are typically greater than 0.3 m/min; material can range from dry to saturated conditions; typically less than 3 m in depth
Rock avalanches	Material that is completely disaggregated into small rock fragments; complex movements that can involve sliding and/or flowing materials in the dry to saturated conditions; velocities are typically greater than 3 m/s; typically greater than 3 m in depth
Rock slumps Soil slumps	Consists of one to several coherent blocks sliding along the shear plane in the dry to saturated conditions; velocities typically range from 1.5 m/yr to 0.3 m/min; typically greater than 3 m in depth
Rock block slides	Consists of one to several coherent blocks experiencing transitional sliding on the shear plane in the moist to saturated conditions; velocities typically range from 1.5 m/yr to 0.3 m/min; typically greater than 3 m in depth
Disrupted soil slides	Numerous small block and individual soil grains and rock fragments; involves translational sliding on a shear plane or layer consisting of weakened and/or sensitive clays; material can range from the dry to saturated conditions; velocities are typically greater than 3 m/s; typically less than 3 m in depth
Soil avalanches	Material that is completely disaggregated into individual soil grains; typically involves translationally sliding with subsidiary flows; material can range from the dry to saturated conditions; velocities are typically greater than 0.3 m/min; typically less than 3 m in depth
Soil block slides	Consists of one to several coherent blocks experiencing translational sliding on the shear plane in the partially saturated to saturated conditions; velocities typically range from 1.5 m/yr to 0.3 m/min; typically greater than 3 m in depth
Slow earth flows	Consists of one to a few coherent blocks experiencing translational sliding in the partially saturated or saturated conditions; velocities range from 0.6 m/yr to 1.5 m/day with surge velocities ranging from 0.3 m/min to 3 m/s; generally, less than 3 m in depth, but can occasionally be greater than 3 m in depth
Soil lateral spreads	Generally consists of several coherent blocks, but can occasionally consist of one to a few coherent blocks or numerous small blocks and individual soil grains and rock fragments in the partially saturated or saturated conditions; velocities are typically between 0.3 m/min to 3 m/s; depths can vary
Rapid soil flows	Material that is completely disaggregated into individual soil grains flowing downslope in the saturated condition at velocities greater than 0.3 m/min; typically less than 3 m in depth
Subaqueous landslides	Typically numerous small blocks and individual soil grains and rock fragments or material that is completely disaggregated into individual soil grains; Can occasionally consist of one to several coherent blocks; material is usually partially saturated or saturated; velocities are typically greater than 0.3 m/min, but can occasionally be between 1.5 m/yr to 1.5 m/day; depths can vary

The relationship between the total area affected by the landslides and the peak ground acceleration is shown in Fig. 3. An upper bound relationship between the total area affected by the landslides and the peak ground acceleration induced by the earthquake is also included in this figure. The data points suggest that the area affected by the earthquake reduces when the peak ground accelerations are greater than approximately 1.2*g*. However, this may be attributed to the examination of landslides over a particular region surrounding the epicenter and the majority of the aftershocks, but not identifying landslides outside of this region. Due to the limited extents of the study area, the area affected by the landslides will also be limited as shown by the reduction in the total area affected by the number of landslides through the data points in Fig. 3.

As both Keefer (1984) and Rodriguez et al. (1999) suggested, the scatter in the points in Figs. 2 and 3 can be attributed to the variations in the seismological and geological factors that will have an impact on the initiation of landslides. Additionally, the geographic characteristics of the area affected by the earthquakes is another important consideration that is disregarded in both Figs. 2 and 3. The geological, seismological, and geographic factors in immediate vicinity of the epicenter will have a substantial influence on the types and number of landslides induced by the earthquake, but all of these influences have not been considered in the preparation of the upper bounds presented in Fig. 2 by Keefer (1984) and Rodriguez et al. (1999) or the upper bound derived in this study in Fig. 3.

Number of Landslides Triggered with Respect to Seismic Intensity

The number of landslides induced by the earthquake should also depend on part on the shaking intensity of the earthquake. However, neither Keefer (1984) nor Rodriguez et al.

Table 3 Characteristics of the observed earthquake-induced landslides based on the information provided in the references cited in Table 1

No.	Earthquake	Rock falls	Rock slides	Rock avalanches	Rock slumps	Rock block slides	Soil falls	Disrupted soil slides	Soil avalanches	Soil slumps	Soil block slides	Slow earth flows	Soil lateral spreads	Rapid soil flows
1	Haiyun													X
2	Daly City		X	X	X	X			X	X	X	X		X
3	Peru	X	X	X		X			X	X	X			
4	San Fernando	X	X	X	X		X	X	X	X				
5	Guatemala	X	X	X	X	X		X	X	X	X			
6	Mammoth Lakes	X	X	X	X			X		X		X		
7	Mt. Diablo	X				X	X			X				
8	Caolinga	X	X		X		X	X		X			X	
9	San Salvador	X	X				X	X		X				X
10	Loma Prieta	X	X		X	X		X		X	X			
11	Loma Prieta	X	X					X						
12	Northridge	X	X			X		X		X			X	X
13	Hyogoken-Nanbu	X	X	X	X	X		X		X	X			
14	Hyogoken-Nanbu	X	X	X	X			X	X	X			X	X
15	Umbria-Marche	X												
16	Umbria-Marche	X	X			X		X			X	X		X
17	Chi-Chi	X	X	X				X	X					
18	Chi-Chi													
19	Chi-Chi	X	X			X		X	X					
20	Avaj	X	X		X	X	X	X			X		X	
21	Mid-Niigata		X	X	X			X	X	X	X		X	
22	Mid-Niigata			X				X	X	X	X	X		X
23	Kashmir	X	X	X				X	X			X		
24	Northern Pakistan	X	X					X	X					
25	Niigata Chuestu-Oki	X	X					X		X	X		X	
26	Pisco	X		X								X		
27	Iwate—Miyagi Nairku		X	X				X	X					X
28	Wenchuan	No information provided in the references.												
29	Wenchuan	X	X	X				X						
30	Port-au-Prince	X	X											
31	Yushu	X						X		X			X	
32	Lorca (SE Spain)	X		X			X	X			X	X		
33	Tohoku	X	X	X	X	X	X	X	X	X		X	X	
34	Gorkha (Main shock)	X	X	X				X				X		X
35	Gorkha (Aftershock)	X	X	X				X				X		X

(1999) have established relationships between the magnitude (or peak ground acceleration) and the total number of earthquake-induced landslides observed. In this section, these relationships will be established using the earthquake events examined in this study.

In the discussions presented in this section, the database has been separated to represent two different landslides scales—moderate to large scale landslides and all landslides. Moderate to large scale landslides refer to, in this study, are any observed landslide that is greater than 100 m^2 in area.

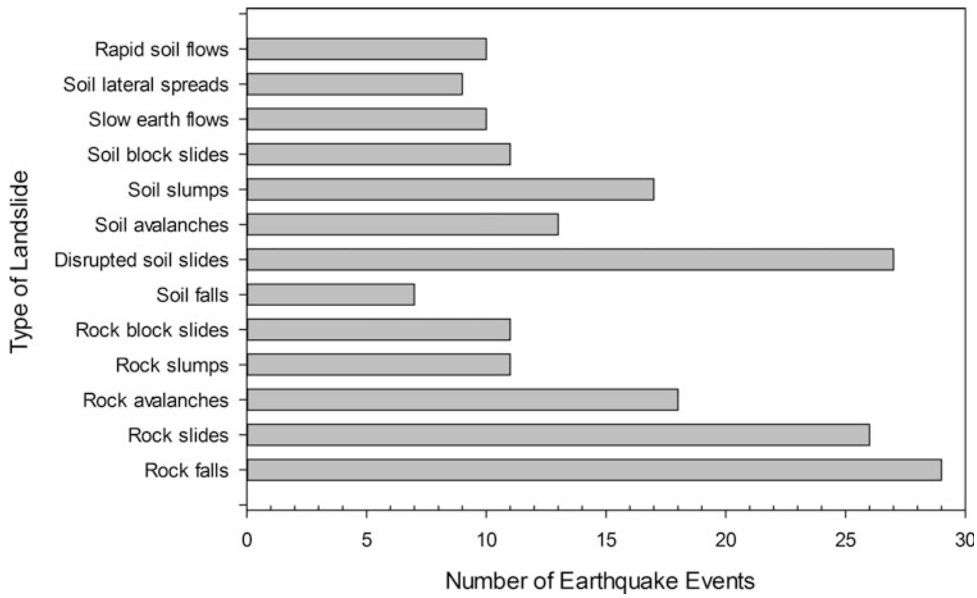

Fig. 1 Frequency of observed landslide types during the earthquake events examined in this study

Table 4 Summary of lower bound values of magnitude and maximum peak ground acceleration to trigger different types of landslides

Category	Magnitude	Max. PGA (g)
All landslides	5.1	0.18
Rock falls	5.1	0.24
Rock slides	5.3	0.18
Rock avalanches	5.1	0.18
Rock slumps	5.3	0.18
Rock block slides	5.3	0.18
Soil falls	5.1	0.36
Disrupted soil slides	5.1	0.24
Soil avalanches	5.3	0.18
Soil slumps	5.3	0.18
Soil block slides	5.1	0.18
Slow earth flows	5.1	0.18
Soil lateral spreads	6.5	0.38
Rapid soil flows	5.3	0.18

This landslide area was a lower bound used in the detection of landslides in many of the studies examined including Sato et al. (2007), Collins et al. (2012), Chigira and Yagi (2006), and Tiwari et al. (2017). However, several sources for the number of landslides indicated that they identified landslides that were significantly smaller than 100 m^2 in area. A couple of authors stated that they were able to identify if a single boulder was displaced by the earthquake. As the damage potential from landslides greater than 100 m^2 in area (or moderate to large scale landslides will be substantially greater (Tiwari et al. 2017; Wartman et al. 2013, among others) than that posed by landslides less than 100 m^2 in area, the two landslide inventories have been separated. The inventories that included landslides less than 100 m^2 in area have been indicated with an asterisk in Table 1.

Figure 4 contains the relationship between the magnitude and the total number of landslides triggered. The data points in Fig. 4 are separated to consider the moderate to large scale landslides separately from the landslides of all sizes. Figure 4 shows an increase in the number of landslides triggered with an increase in the magnitude of the earthquake when considering all landslides as well as just the moderate to large scale landslides. However, a clear relationship between the number of landslides and magnitude is not evident in Fig. 4.

The relationship between the peak ground acceleration and the number of landslides is presented in Fig. 5. Again, the data points are separated on whether the database was developed considering only moderate to large scale landslides or landslides of all sizes. Two clear relationships

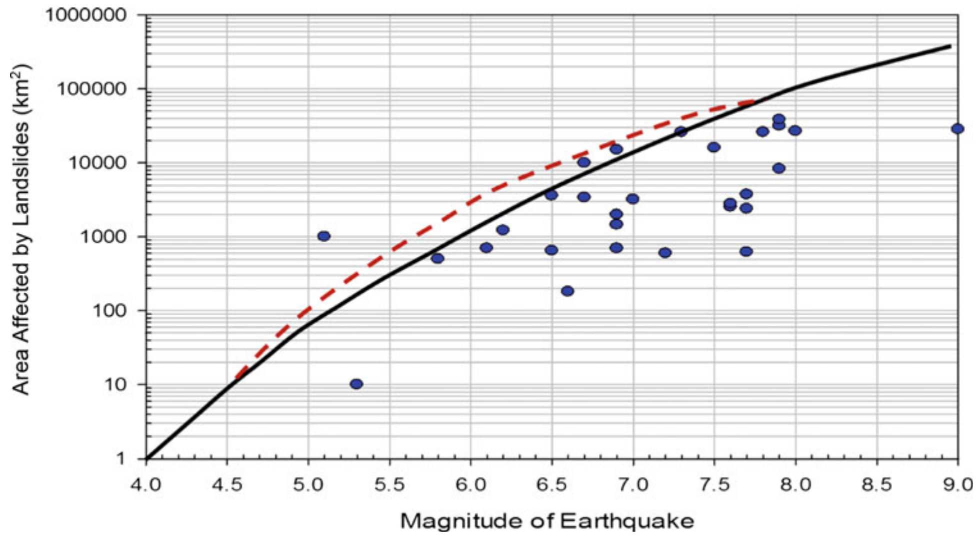

Fig. 2 Relationship between the total area affected by the earthquake-induced landslides and the magnitude of the earthquake; *solid line* is the relationship proposed by Keefer (1984) and *dashed line* is the revision to the relationship proposed by Rodriguez et al. (1999)

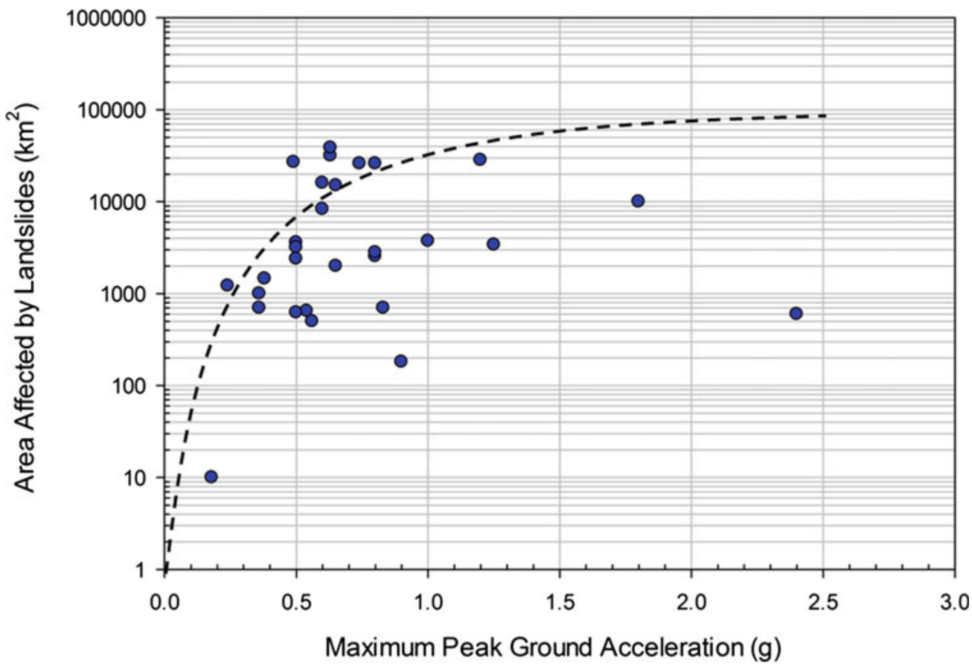

Fig. 3 Relationship between the total area affected by the earthquake-induced landslides and the peak ground acceleration

between the number of landslides and the peak ground acceleration are evident in Fig. 5. These relationships correlate the peak ground acceleration with the number of moderate to large scale landslides (Eq. 1) and with the total number of landslides of any size (Eq. 2) triggered by the earthquake. The resulting relationships are included in Fig. 5. In Fig. 5, there are two points that considered landslides of all sizes that appear to be outliers from the proposed relationship. Upon examination of these two data points, both studies identified the movement of extremely small landslides (even boulders) as a landslide. This will result in a significantly large number of landslides. It is expected that if such small landslides were removed the database the total number of landslides would reduce and the resulting points would lie closer to the proposed relationship.

It is clear that the relationships between the peak ground acceleration and the number of landslide contain less scatter than the relationship between the magnitude of the earthquake and the number of landslides. Moreover, the peak ground acceleration will directly impact the stability of a slope subjected to dynamic loading (Duncan et al. 2014). Therefore, the use of the peak ground acceleration in deriving relationships should be preferred over the magnitude of the earthquake.

$$N = 2223.2(PGA)^{2.13} \tag{1}$$

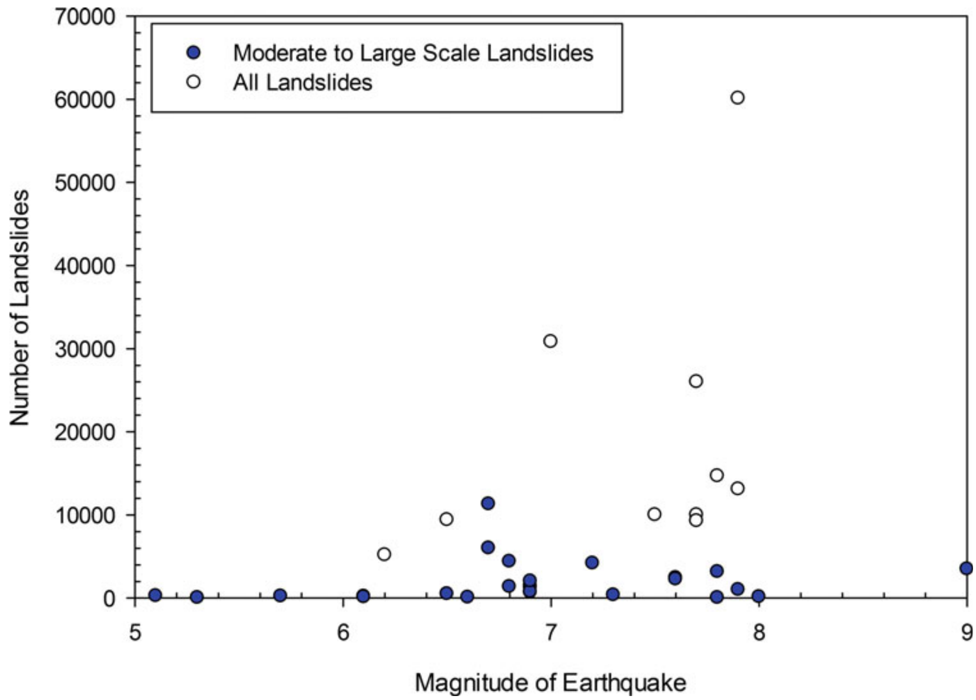

Fig. 4 Relationship between the number of landslides triggered and the earthquake magnitude; *open circles* represent points in the database that considered all landslides (points with an asterisk in Table 1), while close circles represent points in the database that considered only moderate to large scale landslides

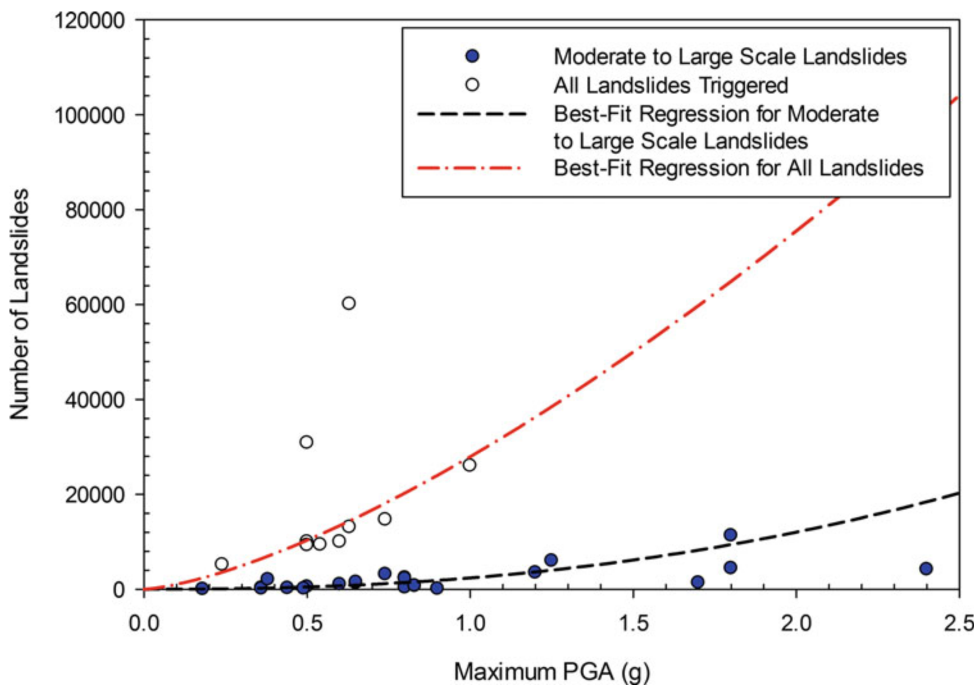

Fig. 5 Relationship between the number of landslides triggered and the peak ground acceleration; Open circles represent points in the database that considered all landslides (points with an *asterisk* in Table 1), while *close circles* represent points in the database that considered only moderate to large scale landslides

$$N = 26{,}967(PGA)^{1.41} \quad (2)$$

where N is the number of landslides of moderate to large scale in Eq. (1) and of any size in Eq. (2) and PGA is the peak ground acceleration in g.

Discussions and Conclusions

Keefer (1984) complied a database that examined 40 earthquake events between 1811 and 1980. This database was extended by Rodriguez et al. (1999), which performed similar analyses as Keefer (1984), using 36 different earthquake events between 1980 and 1994. The database compiled by Keefer (1984) and Rodriguez et al. (1999) has been further extended in this study to include an additional 35 earthquake events from 1920 to 2015 to increase the database from 76 to 111 earthquake events. The analysis of the new database and comparison with the results from Keefer (1984) and Rodriguez et al. (1999) typically agrees with the findings in both of these previous studies. The modification of the relationship between the total area affected by the landslides by Rodriguez et al. (1999) to the original relationship given by Keefer (1984) agrees with the new database for earthquake events used in this study. In addition, a new relationship between the peak ground acceleration and the total area affected by landslides has also been proposed in this study.

Another important contribution from this study is the derivation of the relationships between the total number of landslides and the magnitude of the earthquake as well as the maximum peak ground accelerations induced by the ground shaking, which has not been considered in the previous studies. In establishing these relationships, the total number of landslides from the earthquake events were divided into two sets, the first set considered the total number of all landslides of any size and the second set considered the total of number of moderate to large scale landslides. Moderate to large scale landslides were defined as those greater than 100 m^2 in area. Using the results, two relationships, as expressed in Eqs. (1) and (2), could be defined between the total number of landslides and the peak ground acceleration.

The results suggest that the use of the peak ground acceleration as opposed to the magnitude of the earthquake is better suited in understanding the characteristics of the landslides. The peak ground acceleration will also give stronger relationships between the total area of the landslides and the total number of landslides induced by the earthquakes in comparison to the earthquake magnitude.

References

Alfaro P, Delgado J, García-Tortosa FJ, Lenti L, López JA, López-Casado C, Martino S (2012) Widespread landslides induced by the Mw 5.1 earthquake of 11 May 2011 in Lorca, SE Spain. Eng Geol 137–138:40–52

Bommer JJ, Rodriguez CE (2002) Earthquake-induced landslides in Central America. Eng Geol 63(3–4):189–220

Bonilla MG (1960) Landslides in the San Francisco South Quadrancle, California. U.S. Geological Survey Open-File Report

Bozzano F, Gambino P, Prestininzi A, Scarascia-Mugnozza G, Valentini G (1998) Ground effects induced by the Umbria-Marche earthquakes of September–October 1997, Central Italy. Proceedings of the eighth international congress of the international association for engineering geology and the environment, pp 825–830

Chigira M, Yagi H (2006) Geological and geomorphological characteristics of landslides triggered by the 2004 Mid Niigata prefecture earthquake in Japan. Eng Geol 82:202–221

Collins BD, Kayen R, Tanaka Y (2012) Spatial distributions of landslides triggered from the 2007 Niigata Chuetsu-Oki Japan earthquake. Eng Geol 127:14–26

Duncan JM, Wright SG, Brandon TL (2014) Shear strength and slope stability, 2nd edn. John Wiley & Sons

Esposito E, Porfido S, Simonelli AL, Mastrolorenzo G, Iaccarino G (2000) Landslides and other surface effects induced by the 1997 Umbria-Marche seismic sequence. Eng Geol 58:353–376

Feng X, Guo A (1985) Earthquake landslide in China. Proceedings of the IV international conference and field workshop on landslides, pp 339–346

Fukuoka H, Sassa K, Scarascia-Mugnozza G (1997) Distribution of landslides triggered by the 1995 Hyogo-ken Nanbu earthquake and long runout mechanism of the Takarazuka Golf Course landslide. J Phys Earth 45:83–90

Gorum T, Fan X, van Westen CJ, Huang RQ, Xu Q, Tang C, Wang G (2011) Distribution pattern of earthquake-induced landslides triggered by the 12 May 2008 Wenchuan earthquake. Geomorphology 133:152–167

Harp EL, Keefer DK (1990) Landslides triggered by the earthquake. U. S. geological survey professional paper 1487, pp 335–347

Harp EL, Jibson RW (1996) Landslides triggered by the 1994 Northridge, California, Earthquake. Bull Seismol Soc Am 86(1B): S319–S332

Harp EL, Wilson RC, Wieczorek GF (1981) Landslides from the February 4, 1976, Guatemala Earthquake. Geological Survey Professional Paper 1204-A

Harp EL, Keefeer DK, Sato HP, Yagi H (2011) Landslide inventories: the essential part of seismic landslide hazard analyses. Eng Geol 122:9–21

Harp EL, Tanaka K, Sarmiento J, Keefer DK (1984) Landslides from the May 25–27, 1980, Mammoth Lakes, California, earthquake sequence. U.S. geological survey miscellaneous investigations series map I-1612

Kamp U, Growley BJ, Khattak GA, Owen LA (2008) GIS-based landslide susceptibility mapping for the 2005 Kashmir earthquake region. Geomorphology 101:631–642

Keefer DK (1984) Landslides caused by earthquakes. Geol Soc Am Bull 95:406–421

Keefer DK (2000) Statistical analysis of an earthquake-induced landslide distribution—the 1989 Loma Prieta. Calif Event 58:231–249

Keefer DK (2002) Investigating landslides caused by earthquakes—a historical review. Surv Geophys 23:473–510

Keefer DK, Manson MW (1998) Regional distribution and characteristics of landslides generated by the earthquake. U.S. geological survey professional paper 1551-C, pp 7–32

Keefer DK, Wilson RC (1989) Predicting earthquake-induced landslides, with emphasis on arid and semi-arid environments. Landslides in a semi-arid environment, Inland Geological Society of Southern California Publications 2(1):118–149

Khazai B, Sitar N (2004) Evaluation of factors controlling earthquake-induced landslides caused by Chi-Chi earthquake and comparison with Northridge and Loma Prieta events. Eng Geol 71(1–2):79–95

Lacroix P, Zavala B, Berthier E, Audin L (2013) Supervised method of landslide inventory using panchromatic SPOT5 images and application to the earthquake-triggered landslides of pisco (Peru, 2007, Mw8.0)

Liao C, Liao H, Lee C (2002) Statistical analyses of factors affecting landslides triggered by the 1999 Chi-Chi earthquake, Taiwan. American Geophysical Union Fall Meeting

Liao HW, Lee CT (2000) Landslides triggered by the Chi-Chi earthquake. Proceedings of the 21st Asian conference on remote sensing, vol 1–2, pp 383–388

Mahdavifar MR, Solaymani S, Jafari MK (2006) Landslides triggered by the Avaj, Iran earthquake of June 22, 2002. Eng Geol 86: 166–182

Marzorati S, Luzi L, De Amicis M (2002) Rock falls induced by earthquakes: a statistical approach. Soil Dyn Earthquake Eng 22:565–577

Medvedev SV (1962) Engineering seismology: (Translated from Russia by Israel Program for Scientific Translations)

Morton DM (1971) Seismically triggered landslides in the area above the San Fernando Valley. U.S. Geological Survey Professional Paper 733, pp 99–104

Morton DM (1975) Seismically triggered landslides in the area above the San Fernando valley. State Calif Div Min Geol Bull 196:145–154

Okimura T, Torii N (1999) A study on slope failures due to Hyogoken-Nanbu earthquake and post-earthquake rainfalls. Proceedings of Sino-Japan second workshop on seismic hazard and mitigation, pp 62–65

Plafker G, Ericksen GE, Concha JF (1971) Geological aspects of the May 31, 1970 Perú earthquake. Bull Seismol Soc Am 61(3):543–578

Qi S, Xu Q, Lan H, Zhang B, Liu J (2010) Spatial distribution analysis of landslides triggered by 2008.5.12 Wenchuan earthquake, China. Eng Geol 116:95–108

Rodríguez CE, Bommer JJ, Chandler RJ (1999) Earthquake-induced landslides: 1980-1997. Soil Dyn Earthquake Eng 18:325–346

Rymer MJ (1987) The San Salvador earthquake of October 10, 1986—geologic aspects. Earthquake Spectra 3:435–463

Rymer MJ, White RA (1989) Hazards in El Salvador from earthquake-induced landslides. Landslides: extent and economic significance, pp 105–109

Sassa K, Fukuoka H, Scarascia-Mugnozza H, Irikura K, Okimura T (1995) Landslides triggered by the Hyogoken-Nanbu earthquake. Landslide News 9:2–5

Sato HP, Hasegawa H, Fujiwara S, Tobita M, Koarai M, Une H, Iwahashi J (2007) Interpretation of landslide distribution triggered by the 2005 Northern Pakistan earthquake Using SPOT5 imagery. Landslides 4:113–122

Sato HP, Sekiguchi T, Kojiroi R, Suzuki Y, Iida M (2005) Overlaying landslides distribution of the earthquake source, geological and topographical data: the Mid Niigata prefecture earthquake in 2004, Japan. Landslides 2:143–152

Sitar N, Bardet JP (2001) Chi-Chi, Taiwan earthquake of September 21, 1999 reconnaissance report. Earthquake Spectra A-17:61–76

Tiwari B, Ajmera B, Dhital S (2017) Characteristics of moderate- to large-scale landslides triggered by the M_w 7.8 2015 Gorkha earthquake and its aftershocks. Landslides:1–22

Tiwari B, Tran D, Ajmera B, Carrillo Y, Stapleton J, Khan M, Mohiuddin S (2016) Effect of pre and post earthquake rainfall events on deformation and stability of slopes. Proceedings of the geotechnical and structural engineering congress, pp 1540–1544

Uzarski J, O'Rourke M, Abrahamson N, Amin N, Goltz J, Lam IP, Tseng WS (2001) The Chi-Chi, Taiwan earthquake of September 21, 1999. Earthquake Engineering Research Institute Earthquake Report

Varnes DJ (1987) Slope movement types and process. In: Schuster RL, Krizek RJ (eds) Landslides—analysis and control. Transportation Research Board Special Report, pp 12–33

Wang MN, Wu HL, Nakamura H, Wu SC, Ouyang S, Yu MF (2003) Mass movements caused by recent tectonic activity: the 1999 Chi-Chi earthquake in Central Taiwan. Inland Arc 12:325–334

Wang WN, Nakamura H, Tsuchiya S, Chen CC (2002) Distributions of landslides triggered by the Chi-Chi earthquake in Central Taiwan on September 21, 1999. Landslides 38(4):318–326

Wartman J, Dunham L, Tiwari B, Pradel D (2013) Landslides in Eastern Honshu induced by the 2011 off the Pacific Coast of Tohoku Earthquake. Bull Seismol Soc Am 103(2B):1503–1521

Wieczorek GF, Jäger S (1996) Triggering mechanisms and depositional rates of postglacial slope-movement processes in the Yosemite Valley, California. Geomorphology 15:17–31

Wilson RC, Wieczorek GF, Keefer DK, Harp EL, Tannaci NE (1985) Map showing ground failures from the Greenville/Mount diablo earthquake sequence of January 1980, Northern California. U.S. geological survey miscellaneous field studies Map MF 1711

Xu C, Xu X, Lee YH, Tan X, Yu G, Dai F (2012a) The 2010 Yushu earthquake triggered landslide hazard mapping using GIS and weight of evidence modeling. Environ Earth Sci 66:1603–1616

Xu C, Xu X, Yu G (2012b) Earthquake triggered landslide hazard mapping and validation related with the 2010 Port-au-Prince. Haiti Earthquake 5(4):1297–1304

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

Yamagishi H, Iwahashi J (2007) Comparison between the two triggered landslides in Mid-Niigata, Japan by July 13 heavy rainfall and October 23 intensive earthquakes in 2004. Landslides 4:389–397

Zhang D, Wang G (2007) Study of the 1920 Haiyuan earthquake-induced landslides in Loess (China). Eng Geol 94:76–88

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