Global Journal of Science Frontier Research: H
Environment & Earth Science
Volume 17 Issue 1 Version 1.0 Year 2017
Type : Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4626 & Print ISSN: 0975-5896

Key Parameters that Contribute to the Occurrence of Earthquake Induced Landslides

By Dyson N. Moses
University of Malawi

Abstract- Earthquakes cause widespread landslides more than other geotechnical hazards. In this study, the controlling factors of earthquake induced landslides are identified and evaluated for the major earthquakes with magnitude ≥ 6.6 that occurred between 1998 – 2015 worldwide. A quantitative technique of data analysis was applied to correlate controlling variables and landslides occurrence to draw their relationship determined by regression coefficient. Data was drawn from secondary sources; scientific and technical papers, technical reports, internet sites and relevant books on landslides. The analysis reveal that earthquake induced landslides spatial distribution has no correlation with earthquake magnitude and peak ground acceleration, but a weak positive correlation with respect to peak ground acceleration times shaking duration and Arias intensity. Earthquake induced landslides occurrence also show a strong correlation with regards to geology, fault type, slope angle and slope height. A negative correlation was established between earthquake induced landslides spatial distribution and the distance from the epicentre and surface rupture.

Keywords: *earthquake induced landslides, magnitude, peak ground acceleration, arias intensity, lithology and slope angle.*

GJSFR-H Classification: *FOR Code: 260206*

KEYPARAMETERSTHATCONTRIBUTETOTHEOCCURRENCEOFEARTHQUAKEINDUCEDLANDSLIDES

Strictly as per the compliance and regulations of :

Key Parameters that Contribute to the Occurrence of Earthquake Induced Landslides

Dyson N. Moses

Abstract- Earthquakes cause widespread landslides more than other geotechnical hazards. In this study, the controlling factors of earthquake induced landslides are identified and evaluated for the major earthquakes with magnitude ≥ 6.6 that occurred between 1998 – 2015 worldwide. A quantitative technique of data analysis was applied to correlate controlling variables and landslides occurrence to draw their relationship determined by regression coefficient. Data was drawn from secondary sources; scientific and technical papers, technical reports, internet sites and relevant books on landslides. The analysis reveal that earthquake induced landslides spatial distribution has no correlation with earthquake magnitude and peak ground acceleration, but a weak positive correlation with respect to peak ground acceleration times shaking duration and Arias intensity. Earthquake induced landslides occurrence also show a strong correlation with regards to geology, fault type, slope angle and slope height. A negative correlation was established between earthquake induced landslides spatial distribution and the distance from the epicentre and surface rupture.

Keywords: earthquake induced landslides, magnitude, peak ground acceleration, arias intensity, lithology and slope angle.

I. Introduction

Earthquakes are among the most destructive natural hazards on Earth. An earthquake can cause a slope to become unstable by the inertial loading it imposes or by causing a loss of strength in the slope materials there by inducing failure. Catastrophic landslides characterised by large and extremely rapid movements are among the most destructive phenomena associated with failure of slopes during earthquakes. Landslides encompass many phenomena involving lateral and downslope movement of earth materials under the influence of gravity, and in most cases also water [1], [2]. According to [3], the horizontal and in fewer cases vertical ground acceleration resulting from seismic shaking exert additional transient shear stresses and increases the ambient pore water pressures through cyclic gravitational loading, thus negatively affecting slope stability.

It has been evidently recognised that loss of lives and damage attributed to earthquakes are to a significant fraction incurred by "secondary" earthquake effects such as tsunami, landslides and liquefaction rather than strong ground motion alone. [4] Estimated that approximately 5 % of all earthquake-related fatalities are a result of seismically induced landslides. [3] Argues that the use of the term "secondary hazards" to characterise these effects is potentially misleading, given that any of subsequent process cascades (downslope and downstream transfer of eroded soil and rock) may incur the highest fraction of total damage eventually. Therefore, in a bid to comprehend factors contributing to the occurrence of seismic slope failures this paper aims at documenting major earthquakes with moment magnitude M_w ≥ 6.6 that occurred between 1998 and 2015 in the world, which triggered landslides and evaluate the factors that contributed to the landsliding activities. In this respect attempts are made to establish relationship between earthquake parameters (magnitude, PGA, focal depth and distance from the epicentre), geology and topographic parameters and earthquake induced landslides (EIL) by carrying out a bivariate analysis of the parameters against EIL.

II. Methodology

A comprehensive and rigorous review of data on landslides induced by major earthquakes (Mw ≥ 6.6) that occurred between 1998 – 2015 in the world and studies of some well documented historical EIL have been considered. Data review entailed collection of all relevant information on EIL by historical major earthquakes in the world presented in Table. 1. In the analysis, some of the minor and major well documented cases like the Aysen, Chile 2007, Avaj, Iran 2002, Northridge, California 1994, the Finisterre Papua New Guinea 1993 and the Loma Prieta USA 1989 respectively for representativeness and validation of the study. Reviewed information include; scientific and technical papers, technical reports, seismological and landslides data by USGS. Valuable data was also gotten from internet sites and relevant books on EIL. In assessment of the EIL the parameters given in Figure 1 were considered.

Author: Instructor, Department of Geography and Earth Science at University of Malawi, Chancellor College.
e-mail: dysonmoses@gmail.com

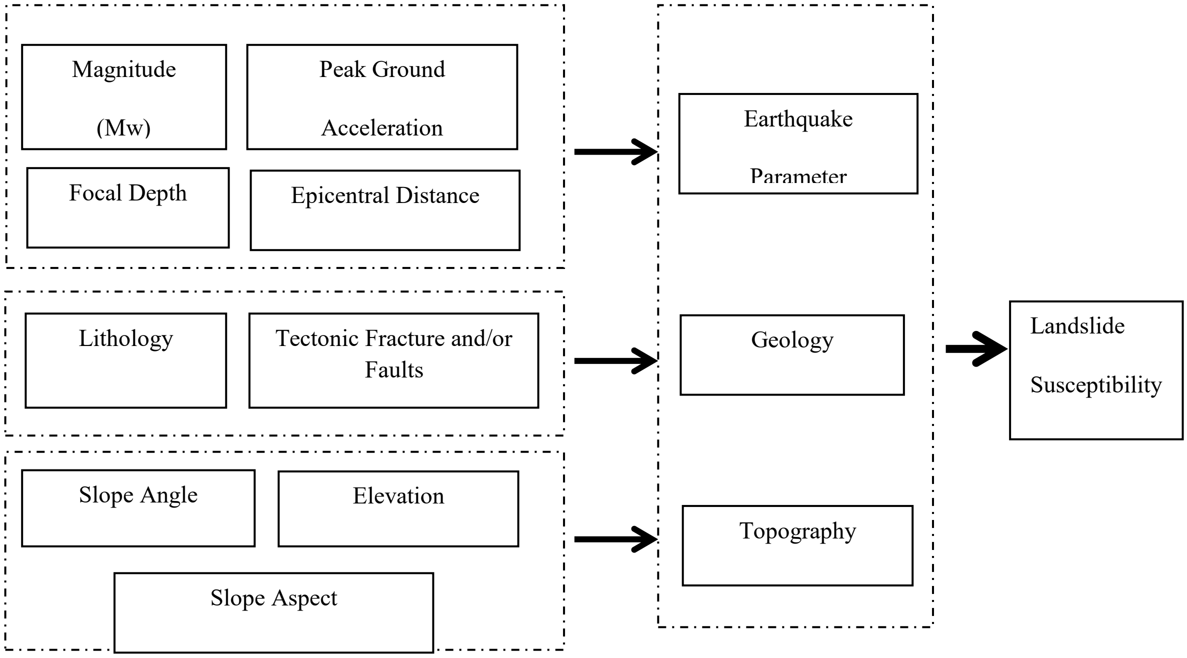

Figure 1: Flow-chart of the methodology used for assessing the EIL

III. Controlling Factors of Earthquake Induced Landslides

Seismic shaking is the principal cause of huge landslides often with disastrous consequences for the people and property concerned [1], [6]. A summary of the major earthquakes (Mw ≥ 6.6) that induced landslides between 1998 and 2015 in the world are presented in Table.1. In addition, 3 major (Northridge, California 1994, the Finisterre Papua New Guinea (PNG) 1993 and the Loma Prieta USA 1989) and 2 minor (Aysen, Chile 2007 and Avaj, Iran 2002) well documented earthquake cases are also presented for implementation and validation of the study. In the table, date of occurrence, name, magnitude, PGA, focal depth, duration of the earthquake, fault type, fault length, reported number of landslides, area affected by landslides and source of data are given. The paper complements the several researchers; [31], [41], [48] [15], [27] and [1]. [32] Stress that it is of primary significance to recognise the conditions that cause slopes to become unstable and the factors that trigger the movement. A great variety of slope movements reflect the diversity of factors that may disturb slope stability. Hence, this section presents the findings of the study.

Table 1: Summary of the major earthquakes that induced landslides between 1998-2015

No	Date	Name	Magnitude (Mw)	PGA (g)	Focal depth (km)	Duration (sec)	Fault Type*	Fault Length (km)	Reported No of Landslide	Landslide area (km2)	Sour ce†
1	25/05/2015	Gorkha, Nepal	7.8	0.35	10-15	50	TF	160	25,000	1,000	[7]
2	20/05/2013	Lushan	6.6	1.00	13	20	TF	35	3,810	2,200	[8]
3	18/09/2011	Sikkim, India	6.9	0.55	10	10	TF	68-119	210	22	[9]
4	11/03/2011	Tohoku, Japan	9.0	0.80	24	360	TF	500	3,477	28,380	[10]
5	14/05/2010	Yushu, China	6.9	0.38	17	15	SSF	30-51	2,036	1,194	[11]
6	12/01/ 2010	Haiti	7.0	0.55	13	30	SSF	65	> 4,490	2,150	[12]
7	27/02/2010	Maule, Chile	8.8	0.65	35	180	TF	500	410	74,131	[13]
8	30/11/2009	Sumatra, Indonesia	8.0	0.60	71	12	TF	60	89	-	[14]
9	12/05/2008	Wenchuan, China	7.9	0.62	19	60	TF	200	>15,000	1,160	[15]
10	14/06/2008	Iwate-Miyagi , Japan	6.9	1.00	8	10	TF	20	4,161	600	[16]

11	21/04/2007	Aysen Fjord, Chile	6.2	0.50	10	-	SSF	12	538	17,000	[17]
12	16/07/2007	Niigata Chuetsu–Oki	6.6	1.01	10	10	TF	39	70	250	[18]
13	15/09/2007	Pisco, Peru	8.0	0.50	39	48	TF	103	866	-	[19]
14	08/10/2005	Kashmir, Pakistan	7.6	0.56	10	25	TF	75	2,424	61	[20]
15	23/10/2004	Mid-Niigata, Japan	6.6	0.48	9-14	30	TF	22	>1,353	250	[21]
16	21/01/2003	Tecoman, Mexico	7.6	0.38	24	30	TF	50	103	-	[22]
17	21/05/2003	Boumerdes, Algeria	6.8	0.58	12	15	TF	36	24	39	[23]
18	22/06/2002	Avaj, Iran	6.5	0.50	7.5	7	TF	13	14,000	3,600	[24]
19	03/11/2002	Denali fault, Alaska	7.9	0.36	5	140	TF	336	10,000	90,000	[25]
20	13/01/2001	Elsavado, USA	7.7	0.60	60	43	TF	65	600	-	[26]
21	21/09/1999	Chi-Chi, China Taiwan	7.5	0.75	33	40	TF	125	>10,000	127.8	[27]
22	17/01/1994	Northridge, California	6.7	0.64	19	20	TF	15	>11,000	10,000	[28]
23	13/10/1993	Finisterre PNG	6.9	0.35	19	20	TF	75	>4,700	55	[29]
24	17/10/1989	Loma Prieta USA	6.9	0.65	19	8-15	OF	35	4,000	15,000	[30]

**TF = Thrust Fault, OF = Oblique-slip Fault, SSF = Strike Slip Fault, = Data unavailabl*

a) Seismic Parameters

The relationship between the seismic parameters of the major earthquakes and reported number of landslides and area affected by EIL has been investigated. Table.2 gives the statistical relations obtained among the seismic parameters of earthquakes and EIL area affected by EIL.

i. *Earthquake Magnitude (M_w)*

According to [1], the strength of the earthquake shaking is a major parameter that determines the occurrence of landslides. Based on this statement, the study endeavoured to establish a relationship between earthquake magnitude and number of landslides. Table.2 shows that there is no relationship found between earthquake magnitude and number of landslides. This highlights the significance of the role played by other factors such as geology and topography in influencing the occurrence of EIL. To assess the likely impact of the EIL in an area, a relationship between earthquake magnitude and area affected by the EIL was tested. The relationship of earthquake magnitude and the area affected by EIL for the major earthquakes (1998-2015) is presented in Figure 2. In this Figure the upper bound curves presented by [5], [33] and [1] are also shown. Plotted values of the investigated EIL areas with respect to the magnitude of earthquakes are clustered below and above the upper bound curves (Figure 2). The plot given in Figure 2 has been extensively but it gives limited information with respect to the trends.

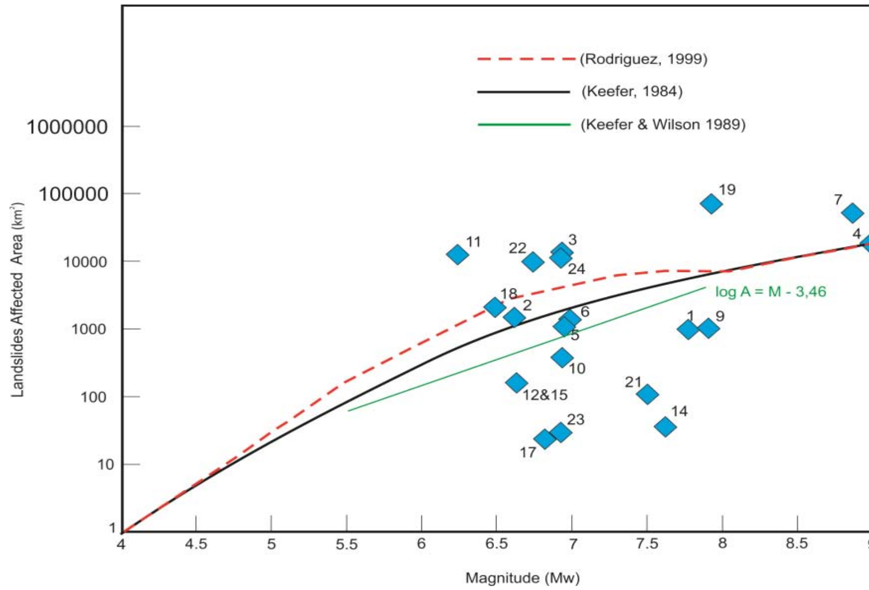

Figure 2: Relationship between earthquake magnitude and the area affected by landslides [5]

In view of this, the study applied a regression approach to establish a relationship between the landslides affected areas and magnitude of studied earthquake. The relationship between the variables yielded a low regression value of $R^2 = 0.40$ (Figure 3) implying that there is a weak correlation between magnitude and the square root of the area affected by EIL.

Table 2: A summary of statistical relationship between seismic parameters and reported landslides and landslides area

Parameters	Reported No of Landslides			Area Affected by Landslides		
	Model fitted	R^2	Comment	Model fitted	R^2	Comment
Magnitude (Mw)	$\sqrt{LN} = -10.679M^2 + 165.22M - 577.58$	0.02	Increasing trend	$\sqrt{LA} = 50.581M^2 - 708.93M + 2528.7$	0.40	Weak Correlation
PGA (g)	$LN = 12285PGA^2 - 21224PGA + 12492$	0.03	No correlation	$LA = -4947.2PGA^2 - 6795.9PGA + 16683$	0.01	No correlation
PGA times Earthquake duration (g*t)	$LN = -2.8329PGA{*}t^2 + 320.31PGA{*}t + 1907.5$	0.20	No correlation	$LA = 0.4931\ PGA{*}t^2 + 651.38PGA{*}t - 2563.3$	0.56	+ve correlation
Arias Intensity (I_A)	$LN = 2E\text{-}05Ia^2 - 0.4406Ia + 5346.2$	0.01	No correlation	$LA = 3814Ia^2 - 157.19Ia - 5795.6$	0.42	Weak Correlation
	$\sqrt{LN} = -3.326Ia^2 + 22.725Ia + 26.816$	0.02	No correlation	$\sqrt{LA} = 15.677Ia^2 - 6.263Ia$	0.45	Weak Correlation
Fault Length (FL)	$LN = 20.082Fl$	0.28	Increasing trend	$LA = 0.1266Fl^2 + 59.006Fl$	0.55	+ve correlation
Focal Depth (D)	$LN = -87.976D + 6601.3$	0.05	No correlation	$LA = -105.79D + 12468$	0.01	No correlation

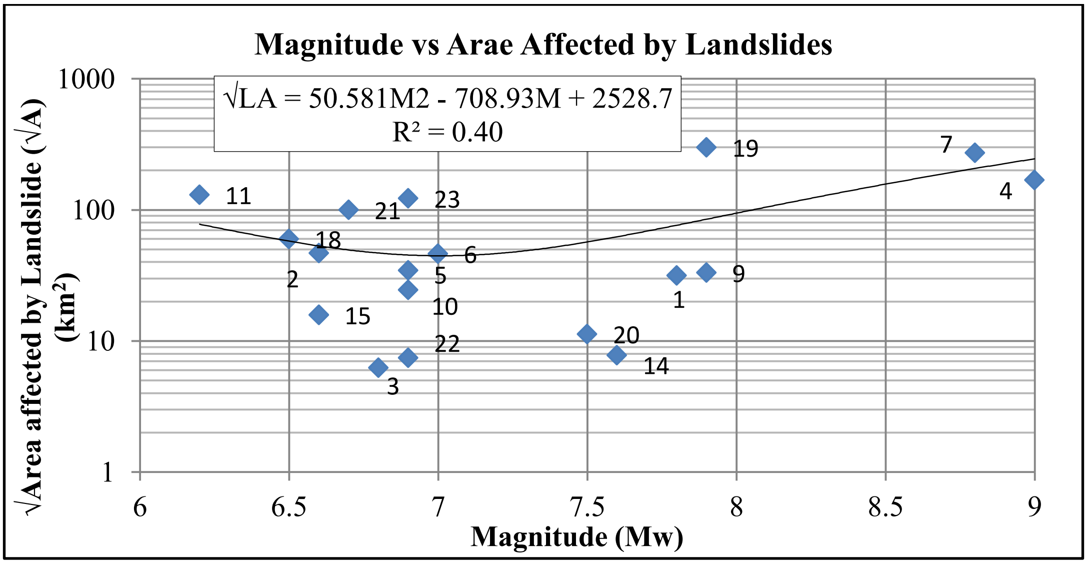

Figure 3: Relationship between the earthquake magnitude and Square root of area affected by EIL

ii. *Peak Ground Acceleration (PGA)*

PGA is a measure that describes the earthquake shaking reasonable to trigger landslides [11]. The statistical analysis between PGA and EIL is shown in Table. 2. The regression analysis indicates that there is no correlation between PGA and occurrence of landslides (Table. 2). For instance, while the Gorkhan, Nepal earthquake of 2015 with a PGA of 0.35g recorded 25,000 landslides the Niigata, Chuetsu-Oki Japan earthquake of 2007 with a PGA of 1.01g only caused 70 landslides. Thus, it is suggested that a good relationship of the two variables can be made if comparisons are made in the same geological and topographic settings. But it is important to point out that there seems to be a threshold value of PGA ≥ 0.3g for landslides occurrence during studied major earthquakes. This threshold PGA value is in agreement with the findings of [27].

Attempt was also made to find out a relationship between PGA and the area affected by landslides and PGA times earthquake duration against the area affected by landslides. Statistical information presented in Table. 2 shows that there is no correlation found between PGA and area affected by landslides. However, a good positive correlation is obtained when the duration of earthquake shaking is included (Table. 2). The coefficient of determination of $R^2 = 0.56$ was obtained when a square root of area affected by landslides is correlated with PGA*t (Figure 4) and a fairly high coefficient of determinatio is obtained when PGA*t is correlated against absolute numbers of landslides induced by earthquakes (Table 2). This indicates that duration of earthquake shaking has a significant effect in as far as EIL are concerned.

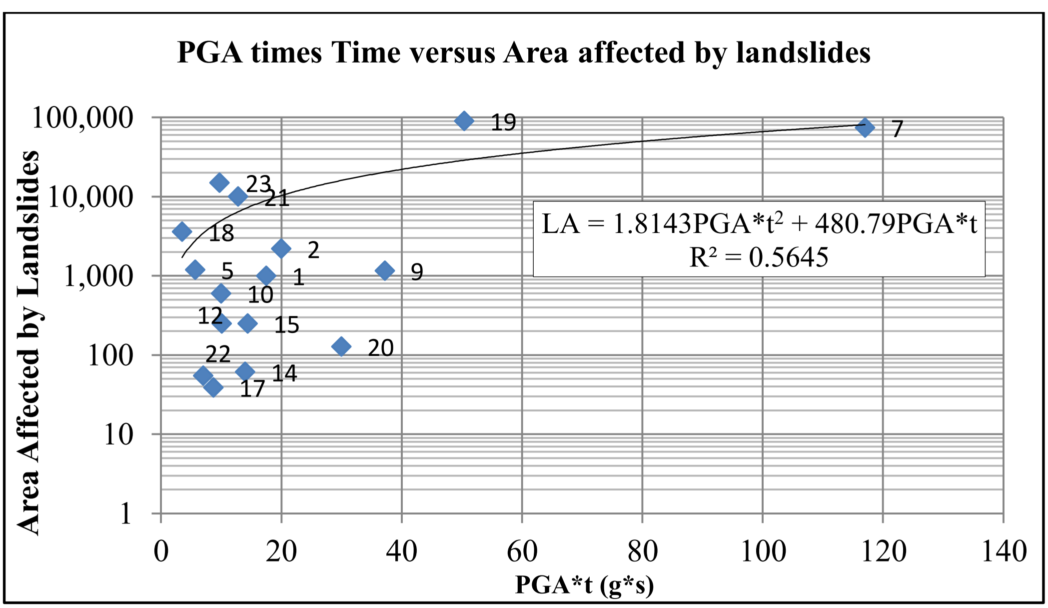

Figure 6: Relationship between PGA*t and area affected by EIL

iii. *Arias Intensity*

The Arias Intensity (I_A) is a measure of the strength of a ground motion developed by Arturo Arias in 1970. The measure was meant to determine the intensity of shaking by measuring the acceleration of transient seismic waves. Despite [39] conviction that I_A is a fairly reliable parameter to describe earthquake shaking necessary to trigger landslides, the measure had not gained support until the work of [35] who used the parameter. Although PGA is still the most commonly used parameter to describe earthquake ground motion, I_A is by far described as an improved seismic parameter [36], [37]. [36] Further explains that the use of the I_A has been proposed to quantify the effect of seismic shaking on ground failure phenomena more effectively. I_A is derived after Arias (1970) in [35] as follows

$$I_A = \frac{\pi}{2g}\int_0^{tf} \alpha(t)^2\, dt \tag{1}$$

Where g is the acceleration due to gravity, a(t) is the recorded acceleration time-history and tf is the duration of the ground motion.

The principal advantage of I_A over PGA is that it measures the total acceleration content of the record rather than just the peak value, providing a more complete characterisation of the shaking energy than PGA [36]. The author further explains that Arias intensity is more objective and comparable from one earthquake to the other, making it a reliable indicator of the capacity of the earthquake shaking to trigger landslides. Thus, the study assessed the impact of I_A in inducing landslides and compares the results against the impact of PGA. The relationship between I_A and area affected by landslides is shown in Figure 5. The results indicate a weak positive correlation with a regression value of $R^2 = 0.45$ between I_A and square root of the area affected by landslides. In contrast, the relationship between PGA and area affected by landslides yielded no correlation. However, when PGA times time of earthquake shaking the coefficient of determination increase to $R^2 = 0.56$. A critical review of the I_A equation shows that it includes time in its derivation. This pattern clearly affirms that earthquake duration plays a key role in causing EIL.

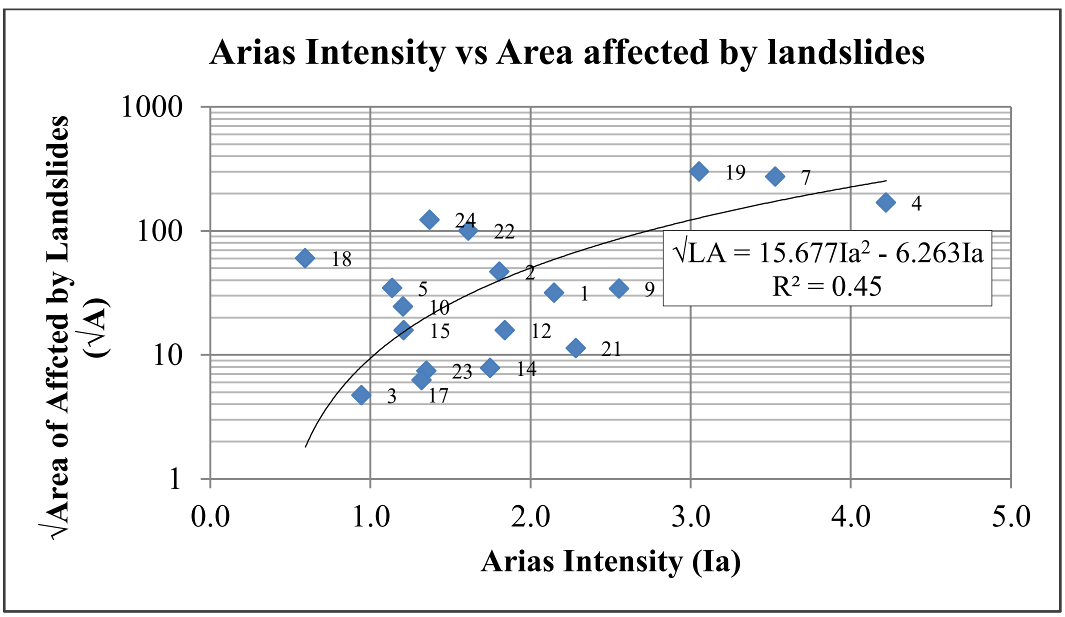

Fig. 5: Relationships between I_A and Area Affected by EIL

iv. *Focal Depth*

Focal depth describes the depth of an earthquake focus to the epicentre. Shallow focus earthquakes (≤ 35 km) are believed to cause widespread landslides than deep focus earthquakes [1]. Based on this statement, the study investigated the correlation between focal depth and area affected by landslides for the major earthquakes in order to understand the impact of focal depth on the occurrence of landslides. The results of the relationship are presented in Figure 6.

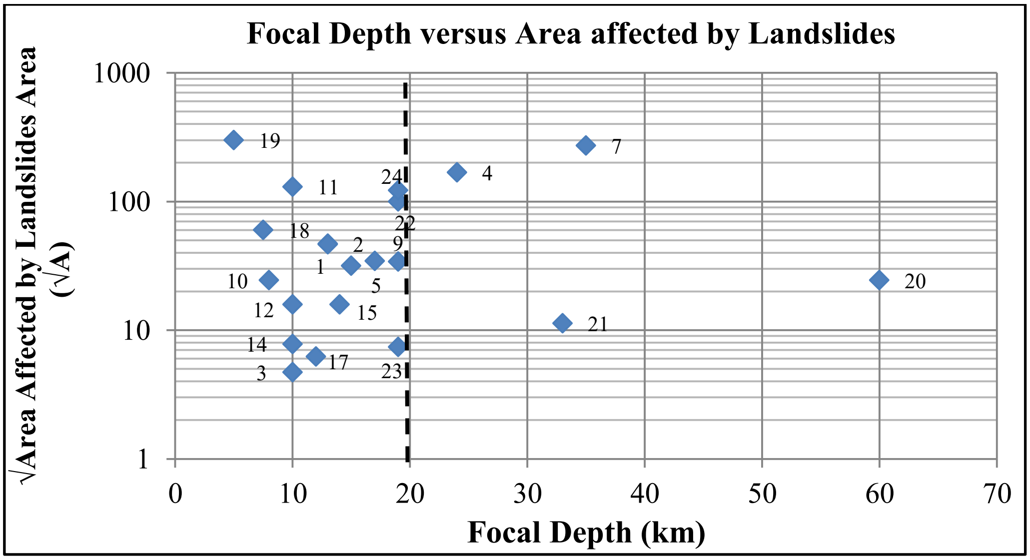

Figure 6: Relationship between focal depth and major EIL

It was observed that there is essentially no correlation between focal depth and EIL nor area affected by landslides, but it is interesting to note that majority of the landslides are concentrated within the depth ≤ 20 km. At depth > 20 km very few landslides are recorded. This finding validates a study by [38] who demostrated that most of the earthquaks that caused landslides had a focal depth of ≤ 35km and as the magnitude of the earthquake increased, they seem to have caused landslides over wider area. However, [33] in their study found some earthquakes that had focal depth > 40 km. This emphasises the dominating influence of other factors other than just focal depth though magnitude was high Mw ≥ 6.5 for studied earthquakes.

v. *Fault Length*

A relationship between fault length and EIL was also investigated. The results are presented in Figure 7. It would be anticipated that the longer the earthquake produced fault length is, the more violently the ground will be shaken, and the more landslides will occur during the earthquake. However, the study established a very weak correlation between the fault length produced by earthquake and number of EIL for the studied earthquakes. The regression coefficient for the correlation is $R^2 = 0.28$ (Table 2). On the other hand, a fairly positive correlation between fault length and area affected by landslides with a coefficient of determination of $R^2 = 0.55$ which shows that fault length has somewhat a significant impact on the area affected by landslides.

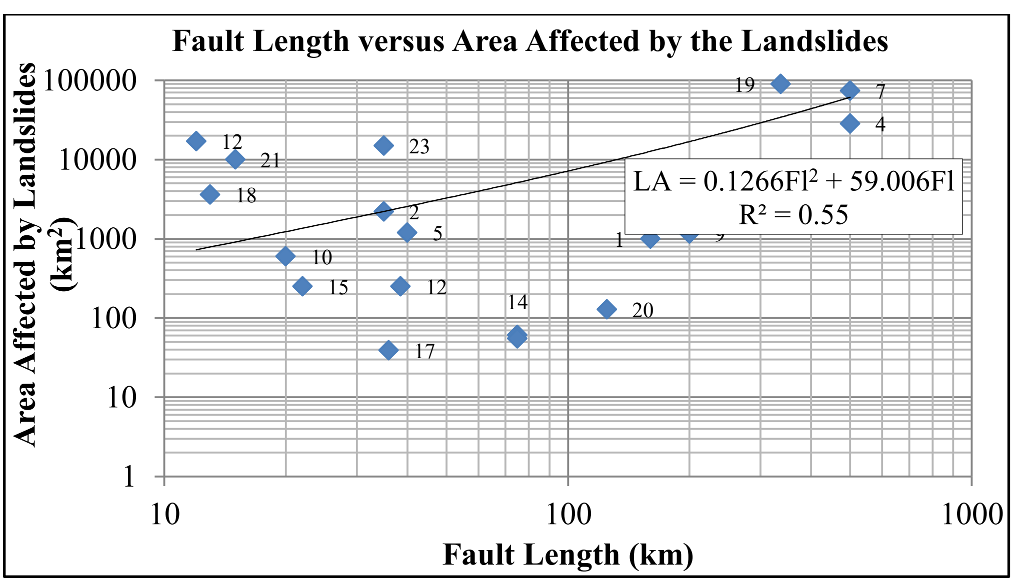

Figure 7: Relationship between fault length and area affected by landslides

vi. *Distance from the Epicentre*

In the scope of the study, efforts were made to establish the impact of distance from epicentre on occurrence of EIL. The findings are presented in Figure 8. EIL distributions as a function of distance from the epicentre indicate that most of the EIL occur within ≤ 50 km from the epicentre. The concentration of EIL gradually decrease with distance away from the epicentre, and landslide concentration values waned beyond the 50 km band for studied earthquakes adopted as epitome of the trend; 2013 Lushan earthquake by and the Italian Catalogue of Earthquake – Induced Ground Failures (CEDIT). The findings corresponded with the results for the Loma Prieta and Chi-Chi 1999 earthquake in which the concentration of landslides waned off at ≤ 60 km band [34].

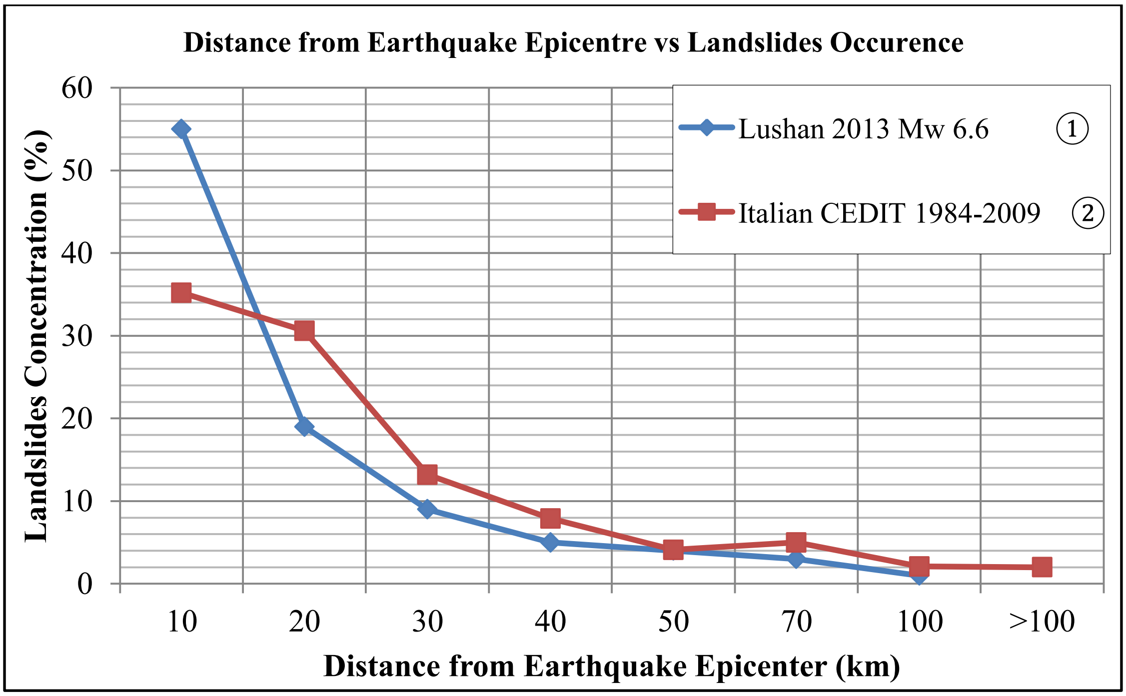

Figure 8: Distribution of landslide with respect to distance from the epicentre (Data from ①[26] and ②[15]

vii. *Distance from the Fault Surface Rupture*

The study also made efforts to understand the influence of distance from fault surface rupture on the occurrence of EIL. A plot of the distance from the fault plane against the EIL concentration is shown in Figure 9. The trend of the distribution reflects that of the distance from the epicentre against landslides. Data analysed from the studies of [41], [44], [15] and [20], show that landslides tend to concentrate on the hanging wall of the thrust faults than on the foot wall but on both walls the landslides concentration decrease away from the fault plane except for the Lushan earthquake, 2013 where the major landslides occurrence took place in the footwall (Figure 9). A similar pattern was found for the Loma Prieta 1989 and Chi-Chi 1999 earthquakes [34].

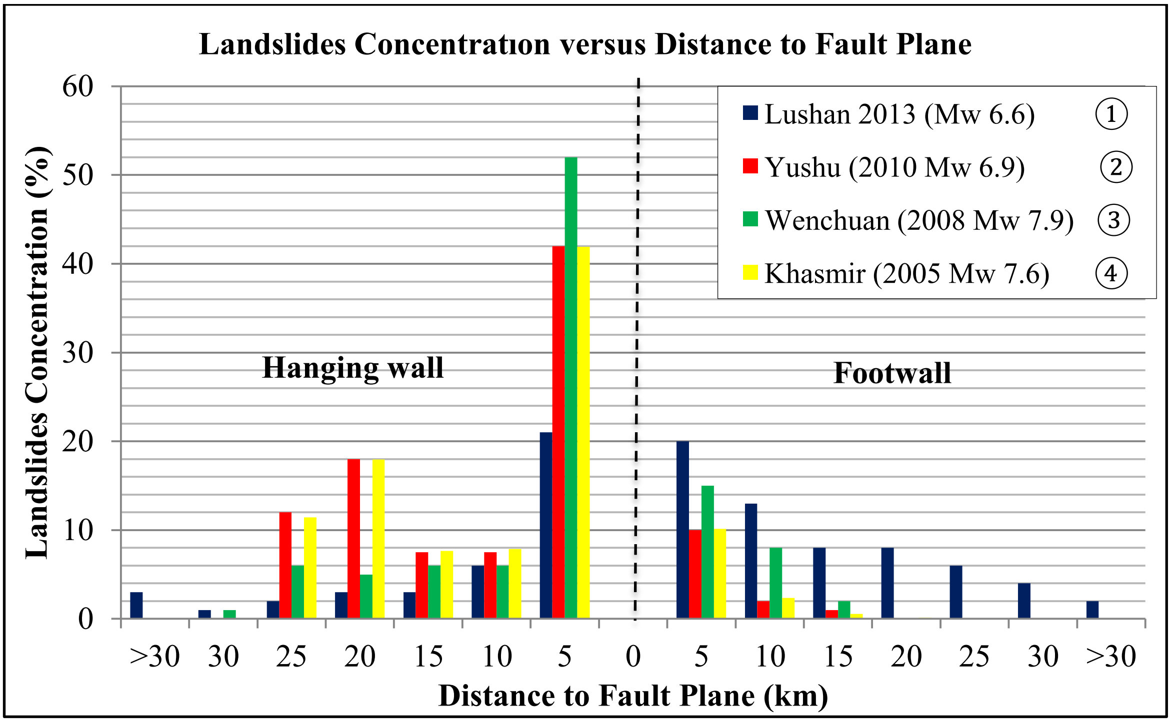

Figure 14: Landslides concentration with respect to distance from the fault plane (Data from ①[41], ②[11], ③[15] and ④[20]

b) Geological Environments

i. *Lithology*

It is widely recognised that lithology plays a significant role in seismic landslides occurrence because strength, structure, composition and related soil and rock properties consisting the slope determine the likelihood of landslides occurrence. Based on the study evaluated the influence of lithologic units on EIL. In this regard, a correlation between geology and landslides was done for 6 major landslides inducing earthquakes presented in Table 1. It can be observed that the distribution of landslides after the Tohoku 2011 earthquake recorded the highest value in the Neogene Sedimentary rocks (42%) followed by Quaternary Alluvium (Figure 10). During the Wenchuan 2008 earthquake, landslide occurrence was concentrated in the Cambrian sandstone and siltstone (49.6%) followed the Silurian slate and phylite (23%) (Figure 11)

Similary, after the 2007 Niigata Chuetsu–Oki Japan Earthquake several units indicate that they were particularly susceptible to landsliding, namely; Pliocene (56%) and Miocene (16%) sedimentary units, typically consisting of sandstones and mudstones, and Pleistocene dune sands (Figure 12). Weakly cemented sands were also particularly susceptible to failure from seismic shaking. In Taiwan, Neogene sandstone and shales after the Chi-Chi 1999 earthquake accounted for over 66% of the landslides induced by the ground shaking (Figure 13). The value is relatively lower than in 1994 Northridge Earthquake in which Tertiary sedimentary rocks accounted for 71% of the total landslides that occurred (Figure 14).

Lastly, for the 1989 Loma Prieta earthquake, sedimentary rocks were most susceptible to producing shallow disrupted landslides. More than 25% of the total landslides were concentrated in the formation, comprising of an interbedded sequence of sandstones, siltstones, and shales (Figure 15). It can be inductively concluded from these cases that Sedimentary rocks, particularly Tertiary sedimentary rocks, are highly susceptible to failure during earthquakes than other lithologic units.

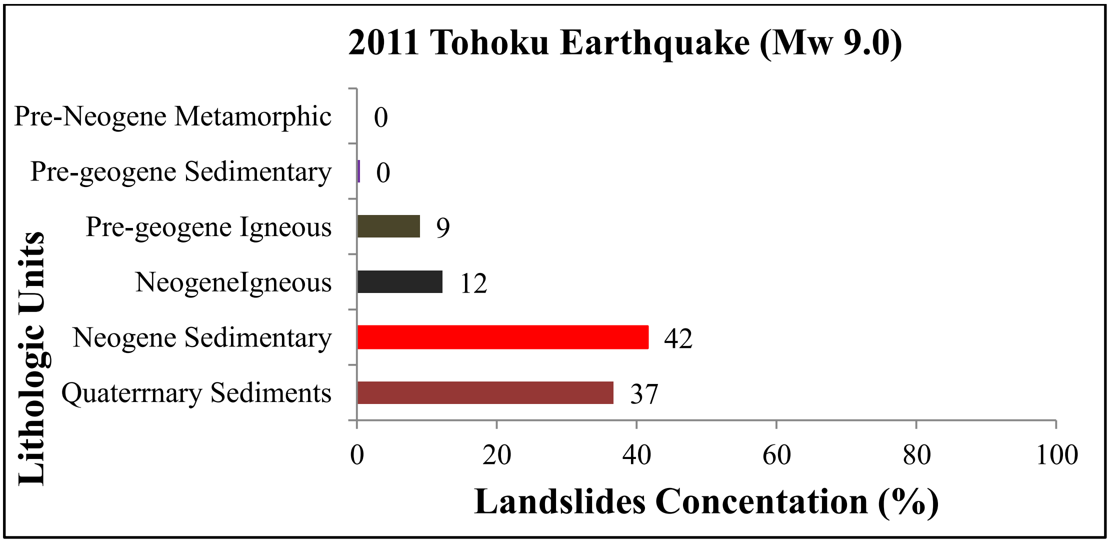

Figure 10: EI landslides concentration with respect to lithology after the 2011 Tohoku Japan earthquake [10]

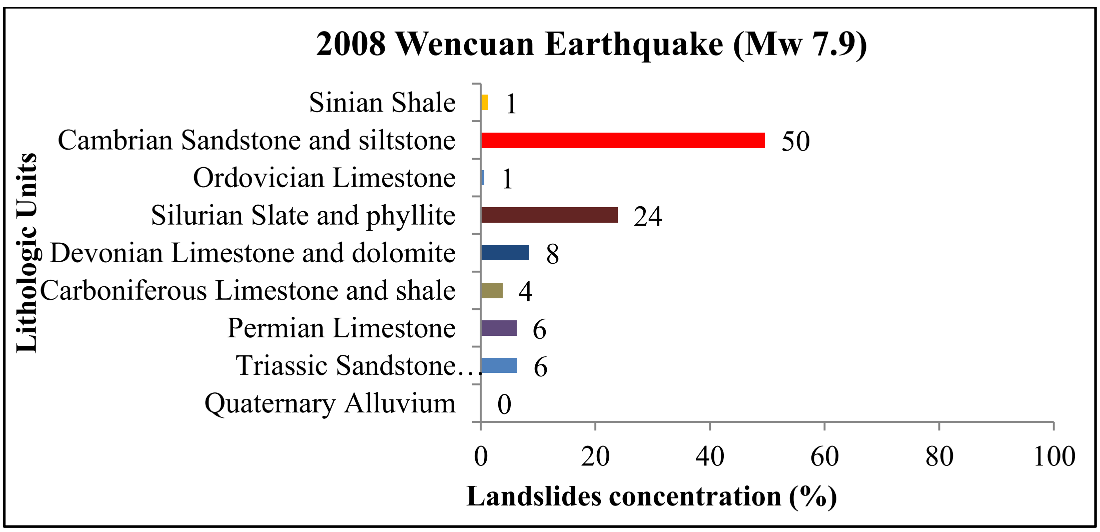

Figure 11: EI landslides concentration with respect to lithology after the 2008 Wenchuan Earthquake [15]

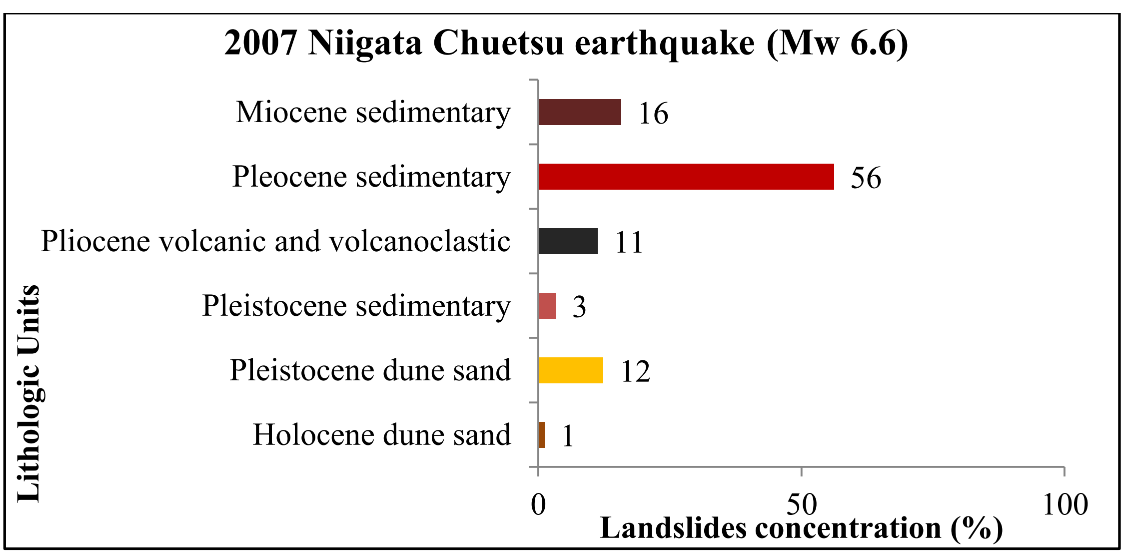

Figure 12: EI landslides concentration with respect to lithology after the 2007 Niigata earthquake after [9]

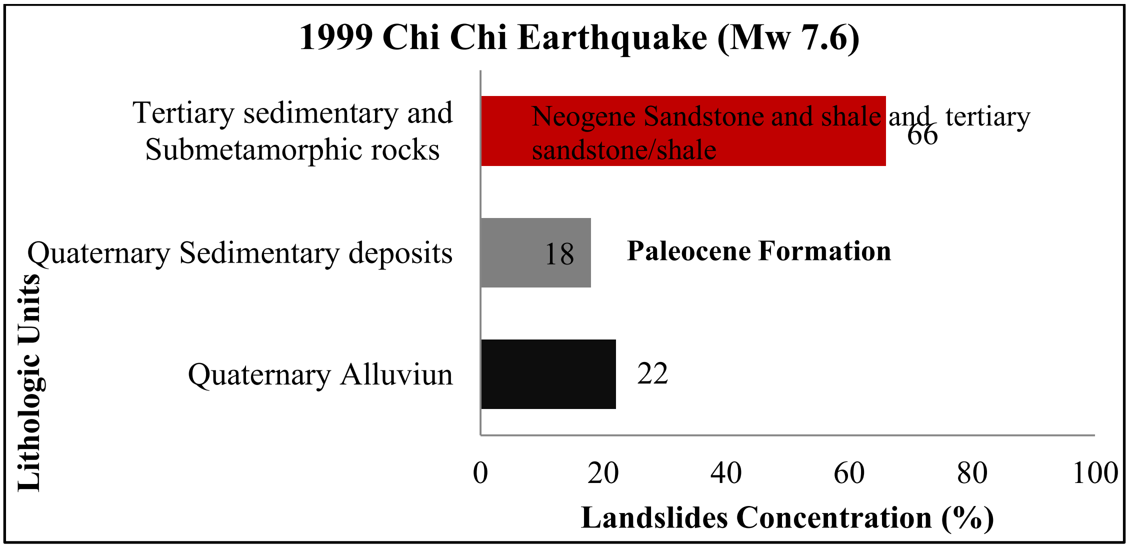

Figure 13: EI landslides concentration with respect to lithology after the 1999 Chi Chi earthquake after [34]

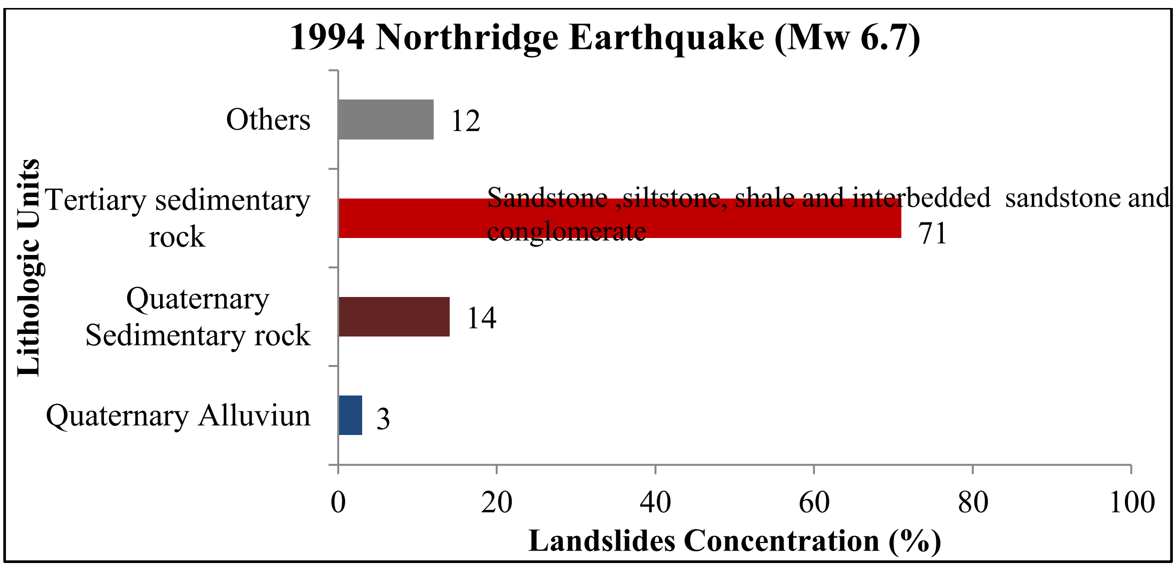

Figure 14: EI landslides concentration with respect to lithology after the 1994 Northridge Earthquake [28]

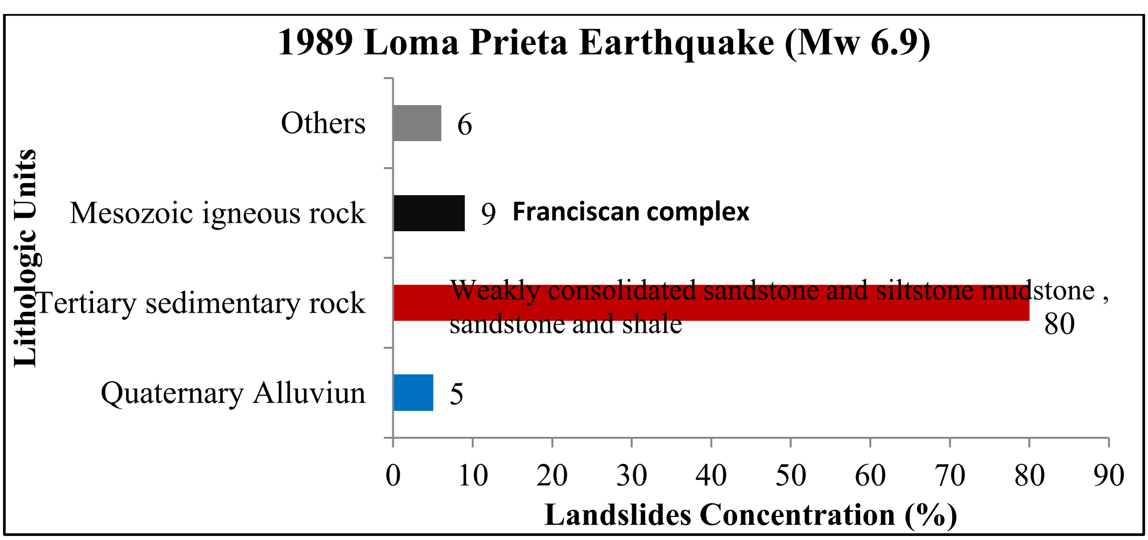

Figure 15: EI landslides concentration with respect to lithology after the 1989 Loma Prieta Earthquake [33]

ii. *Fault Type*

Fault types were analysed to assess their impact on the occurrence of landslides after an earthquake. The relationship between fault type and landslides generating earthquakes is presented in Figure 16 using the information from Table.1. It can be observed in Figure 16 that occurrence of landslides is strongly related to thrust fault type. Earthquakes on thrust faults recorded a frequency of 83% and have caused mass landslides of 91% of the total landslides generating earthquakes investigated followed by earthquakes that occurred on strike slip faults (6%) with a frequency of 13% and the least of the earthquake that induced landslides are on oblique fault with 3% of the total reported landslides and 4% frequency of earthquake occurrence.

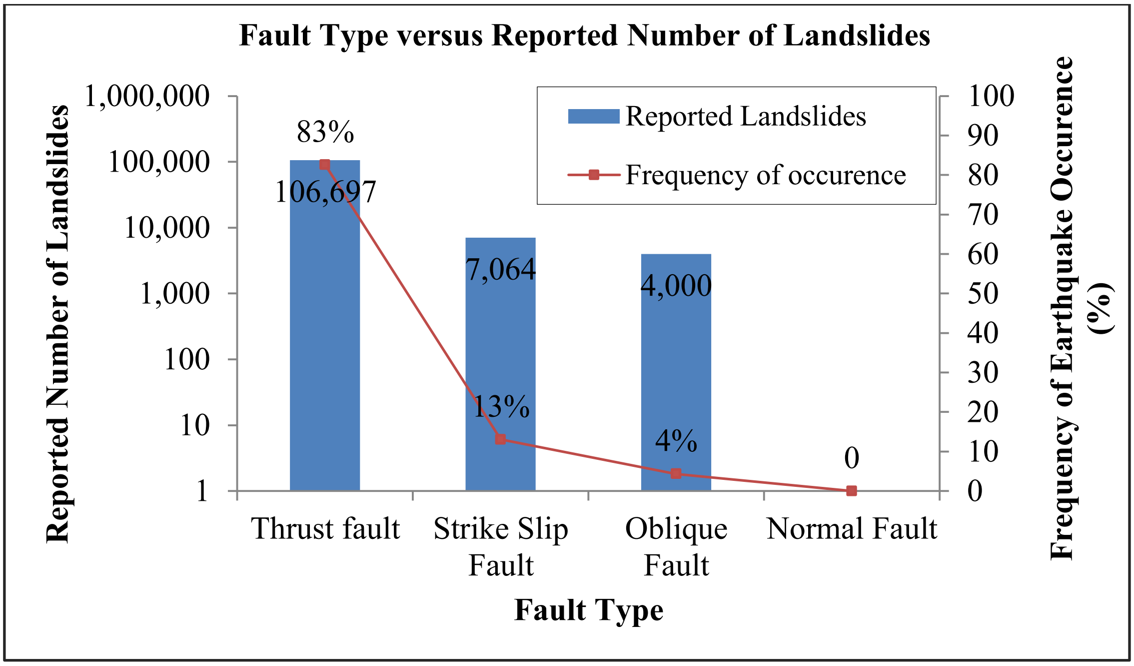

Figure 16: Relationship between fault type and reported number of landslides and their frequency (Source Table 1)

c) *Topography*

i. *Slope Angle*

Slope angle is one of the main factors that influence occurrence of landslides. [34] Argue that of all attributes of topography; slope angle is likely to be the strongest control on landsliding. Hillslope failures occur when the shear stress across a potential failure plane exceeds the substrate strength. Fundamentally, the stability of a hillslope is determined by its surface gradient, the density, cohesion and frictional properties of its substrate, the depth of potential failure plains, and the gravitational acceleration [34]. Slope angle of the EIL against the landslides concentration for the investigated major earthquakes from Table.1 have been presented in Figure 17.

Figure 17 shows that the trend line for Lushan 2013 earthquake recorded a peak landslides concentration the 40°-50° category and then declined with increase in slope angle. For Yushu 2010 earthquake, landslides are concentrated in the 40-50° category. However, the data on slope angle and landslides concentration for Yushu 2010 earthquake as presented by [11] was clumped for slope angles from ≥ 40 degree. The trend line for Wenchuan 2008, Niigata Chuetsu Oki 2007, Kashmir 2005 and Northridge 1994 earthquakes show a common trend where landslides concentration increases with increasing slope angle until the maximum is attained in the 30°–40° category, and then decreases steadily with increasing slope gradient. This implies that if the data for Yushu 2010 earthquake was provided for 40°-50° category and above the trend line would have similar pattern of Wenchuan 2008, Niigata Chuetsu Oki 2007, Kashmir 2005 and Northridge 1994 earthquake.

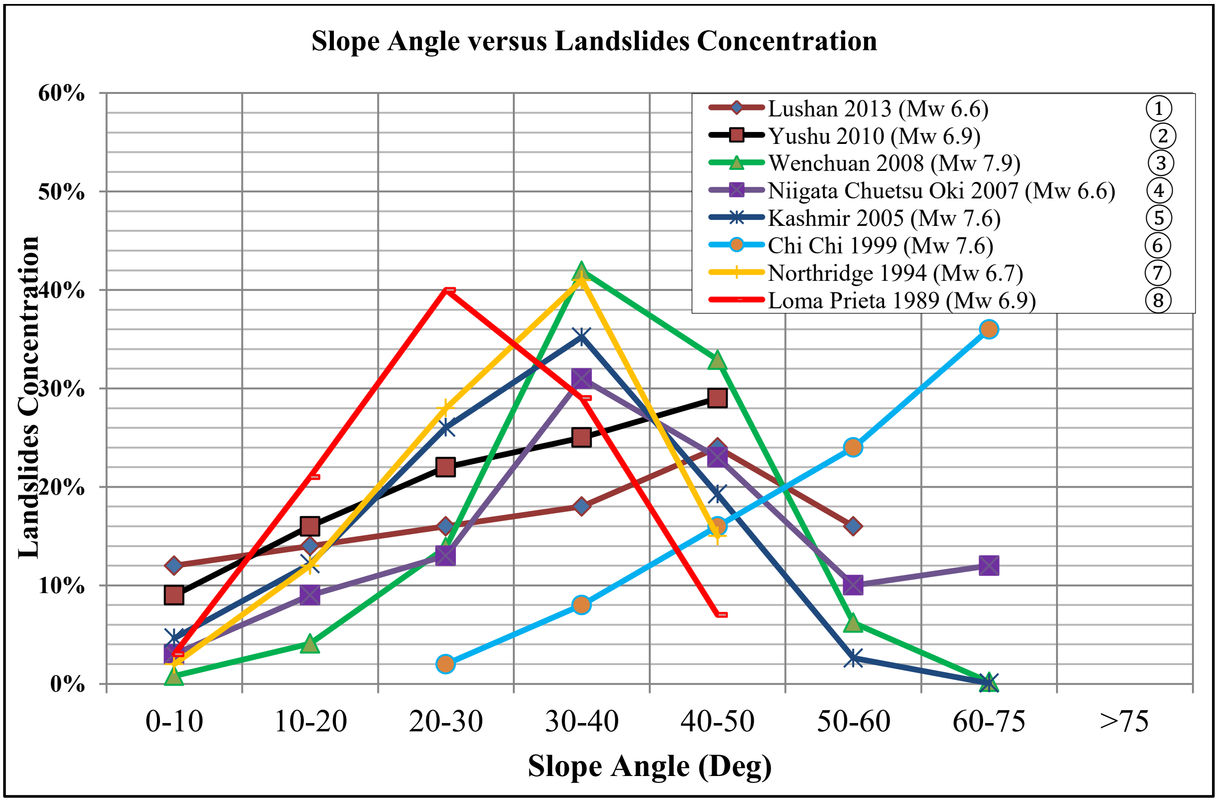

Figure 17: EIL concentration with respect to slope angles in degrees (Data from [8] ①, [11] ②, [15] ③, [9] ④[20] ⑤ [34] ⑥, [28] ⑦ and [33] ⑧)

In the case of the Chi-Chi 1999 earthquake, the landslides concentration increased continually in correspondence with the increasing slope angle. [34] Attribute this deviant trend of the Chi Chi 1999 landslides distribution to the fact that the steep slope angles of the young mountain ranges in Taiwan reflected the dominant type of failure since disrupted slides and toppling/rock falls typically occur on such kind of steep slopes.

ii. *Slope Height*

The impact of slope height cannot be ignored in the study of EIL. Elevation disparities and associated vegetation, weathering, slope material moisture content, and seismic wave amplificaton effect can control seismic landslides [42]. The histogram for elevetion and EIL concentration for representative Yushu, 2010, Wenchuan 2008 and Kashmir 2005 earthquakes is presented in Figure 18. The results of the studied earthquakes show that the highest landslides values occurred at elevations from 750 m to 1500 m, and the values started declining as elevations increase above 1750 m.

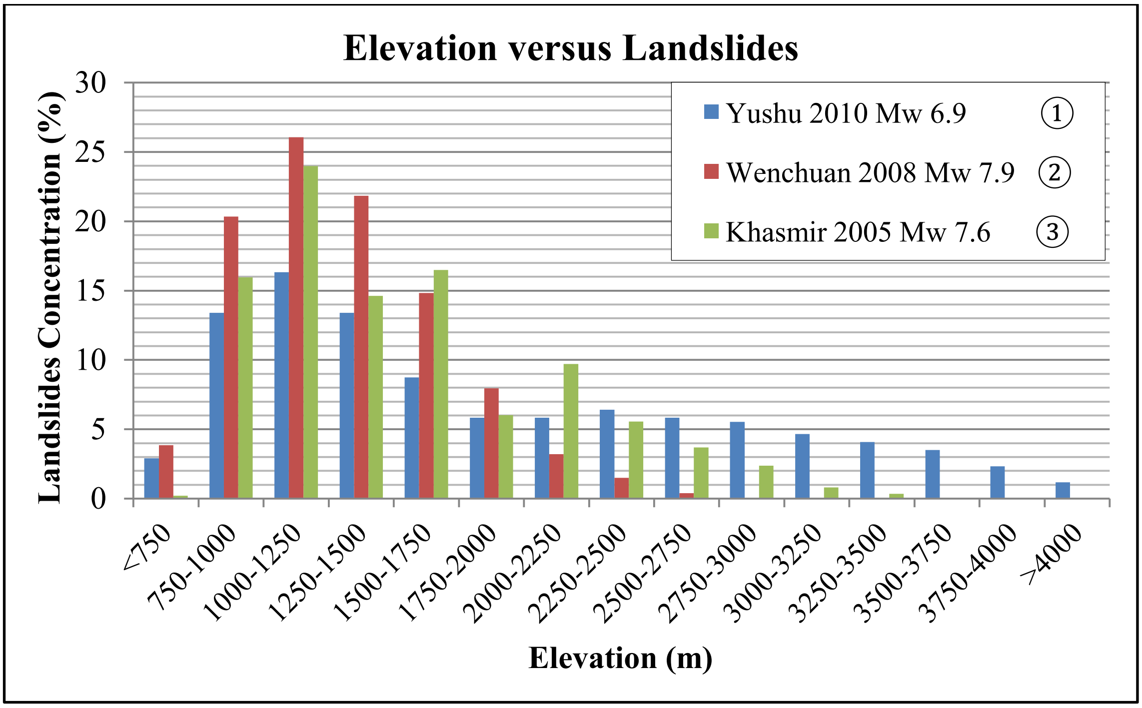

Figure 26: Distribution of landslides with respect to elevation; (Data from [11] ①, [15] ② and [31] ③)

IV. Discussion

In this technical analysis, the principal factors for landslides occurrence due to major earthquakes Mw ≥ 6.6 that occurred between 1998 – 2015 in the world, have been investigated. A quantitative technique of data analysis employed in this study to correlate variables so as to establish their relationship indicate that covariates found to be significantly associated with EI landsliding were; earthquake magnitude, peak ground acceleration and earthquake duration, proximity to the epicentre and/or fault rupture, geology, slopes angle and elevation.

The study has shown that earthquake magnitude has a weak correlation with the area affected by the landslides. However, when the earthquake magnitude are plotted against the square root of the landslides area, a better correlation with a regression coefficient of R^2 = 0.40 was obtained implying somewhat a significant influence of magnitude on area affected by EIL. The occurrence of landslides as a function of earthquake ground shaking reveals that PGA alone has no major influence unless it is combined with earthquake shaking duration. Similarly I_A gives a strong relationship with the EIL area since it incorporates the dimension of earthquake duration in the derivation of the parametric value. Focal depth also demonstrated an impact on the occurrence of EIL; swallow depths can be considered as a significant ingredient for occurrence of landslides which affect a considerably wide area as majority of the earthquakes that induced landslides recorded a depth ≤ 20 km.

Earthquakes at great depth in the ground virtually do not cause imminent landslides as the energy becomes lethargic upon reaching the surface of the earth [38]. The review of other studies show that earthquakes with a focal length of ≤ 35 km are likely to cause more landslides than deep seated ones although earthquakes with focal depth ≥ 35 might be register landslides. Landslides distribution as a function of distance from the epicentre and distance from the surface fault plane indicate that most of the landslides occur within 50 km from epicentre and/or fault plane and drastically reduce further away. This can be attributed to the attenuation of energy as the seismic waves travel through the ground.

In terms of geology, the analytical study revealed that geological setting has a great influence on occurrence of landslides during an earthquake. The main lithologic unit prone to landsliding due to seismic effect are the Tertiary sedimentary rocks with at least over 50% of landsliding concentration (Figures 10 - 15). Landslides also occur in metamorphic and igneous rocks if they could be weakened enough by discontinuities and/or weathering. Quaternary lithologic units recorded low landslides because they are usually in peneplains. However they could be prone to liquefaction if the loose sand and silt saturated are strongly shaken long enough by an earthquake causing them to behave like a liquid. It has also been discovered that landslides are strongly correlated to thrust fault type. Thrust fault type tends to register a high proportion and frequency of EIL seconded by strike slip fault type. This is because at thrust faults, compressional forces cause the blocks on the fault plane to collide violently as the hanging wall runs over the foot wall during its upward movement along the fault plane. Interestingly, no landslides have been reported to have occurred on normal faults for the studied cases. This contrasting phenomenon is attributable to non-violent nature of the extensional forces operating on normal faults that might induce imperceptible deep seated failures with creeping effect. Furthermore, the hanging wall of the thrust fault generally tends to have a higher number of EIL than the foot wall of the thrust fault since it is the block that has relatively high motion. On the other hand, the strike slip fault tends to have almost an equal distribution of EIL on both sides of the fault ruptures.

Geographical environments cannot be ignored when considering seismically induced landslides. The paper has shown the general trend is such that landslides concentration increases corresponds with increasing slope angle until the maximum is reached in the 30°–40° category, and then decreases as slope gradient keeps increasing. It is also worth mentioning that the tendency of the slope to sliding is generally heightened by undercutting action of a river, proximity to drainages and roads as discussed by [43]. Regarding elevation, the results have shown that landslides increase with increasing slope elevation from 750m until the maximum is reached in the 1200–2500m range and then decrease as such heights are surpassed. Due to the complexity and negligible influence of slope aspect and curvature, the study did not focus but other studies might be conducted in that respect. These parameters have a strong reliance on location of the epicentre that determines the distribution of the seismic waves hence the outcomes are variant in individual earthquakes

V. Conclusion

The bivariate analysis applied in the study has demonstrated that no single factor could be picked out as the dominant causative agent of the EIL over the others because the effectiveness of one factor in inducing landslides is dependent on the other factors. Aside the interdependence of the controlling factors, the review of literature has shown that many earthquakes do not cause imminent landsliding activities. However, the earthquake cause slopes to become unstable by the inertial loading it imposes or by causing a loss of strength in the slope materials. so, when heavy rains pour down the ground shaking impact by an earthquake will have created conducive conditions for landsliding as was the case after the Chi-Chi earthquake [46]. Consequently, long-term landslide vulnerability assessments tend to under-represent EI landslide risks as the emphasis is typically put on rainfall-induced landslide events. Under-representation of EIL also comes from the complexity of the analysis because it involves numerous fields such as geology, geophysics, seismology and geotechnics as observed. Thus it is recommended that long-term EIL vulnerability assessments need to be intensively researched on.

References Références Referencias

1. Keefer, D. K. (1984). Landslides caused by earthquakes. *Geological.Society of.America.Bull. 95*, 406-421. United States Geological.
2. Walker, B.F. & Fell, R. (1987). *Landslide classification, geomorphology and site investigation.* Induced Balkema Rotterrdam.
3. Korup, O. (2010). *Earthquake-triggered landsldes Spartial pattern and impacts*. Swiss Federal Research İnstitutes WSL/SLF, CH-7260 Davos.
4. Budimir, M. E. A., Atikson, P. M., & Lewis, H. G. (2015). Seismically-induced landslides hazards and exposure modelling in southern California based on the 1994 Northridge, California earthquake event. *Landslides 12*, 895-910. Springer Verlag Berlin Heidelberg
5. Rodrigues, C. E, Bommer, J. J., & Chandler, R. J (1999). Earthquake induced landslides: 1980 – 1997. *Soil Dynamics and Earthquake Engineering 18*, 325-346.
6. Anderson, M. G., & Richards, K. S. (1989). *Slope stability; geotechnical engneering and geomorphology.* New York: John Wiley and Sons Ltd.
7. Aydan, O., & Ulusay, R. (2015). A quick report on the 2015 Gorkhan (Nepal) Earthquake and its geo-engineering aspects. *International Association for Engineering Geology and the Environment 10,* 25-35.
8. Tang, C., Ma, G., Chang, M., Li, W., Zhang, D. et al. (2015b). Landslides triggered by the 20 April 2013 Lushan earthquake, Sichuan, *Engineering Geology 187*, 45–55.
9. Chakraborty, I., Ghosh, S., Bhattacharya, D., & Bora, A. (2011). Earthquake induced landslides in the Sikkim-Darjeeling Himalayas - An aftermath of the 18 th September 2011 Sikkim earthquake. *Soil Dynamics and Eartquake Engineering 07*, 1–8.
10. Hashmoto, M., Fukushima, Y. & Takada, Y. (2012). Coseismic deformations of the 2011 Tohoku, Japan, earthquake and triggered events derived from Alos / Palsar. *Disaster Prevention Research Institute 661,* 5-9. *Fringe 2011* Workshop (ESA SP-167, 2012)
11. Xu, C., & Xu, X. (2014a). Statistical analysis of landslides caused by the Mw 6.9 Yushu, China, earthquake of April 14, 2010. *Natural Hazards 72*, 871–893. http://doi.org/10.1007/s11069-014-1038-2
12. Gorum, T., van Westen, C. J., Korup, O., van der Meijde, M., Fan, X. et al. (2013). Complex rupture mechanism and topography control symmetry of mass-wasting pattern, 2010 Haiti earthquake.

Geomorphology 184, 127–138. http://doi.org/10.1016/j.geomorph.2012.11.027

13. Delgado, J., Garrido, J., López-casado, C., Martino, S., & Peláez, J. A. (2011). On far fi eld occurrence of seismically induced landslides. *Engineering Geology, 123*, 204–213. http://doi.org/10.1016/j.enggeo.2011.08.002
14. Umar, Z., Pradhan, B., Ahmad, A., Neamah, M., & Shafapour, M. (2014). Earthquake induced landslide susceptibility mapping using an integrated ensemble frequency ratio and logistic regression models in West Sumatera Province, Indonesia. *Catena 118*, 124–135.
15. Qi, S., Xu, Q., Lan, H., Zhang, B., & Liu, J. (2010a). Spatial distribution analysis of landslides triggered by 2008 . 5 . 12 Wenchuan. *Engineering Geology 116* (1-2), 95–108. http://doi.org/10.1016/j.enggeo.2010.07.011
16. Yagi , H., Sato , G., Higaki, D., & Yam, M. (2009). Distribution and characteristics of landslides induced by the Iwate–Miyagi Nairiku Earthquake in 2008 in Tohoku District, Northeast Japan. Landslides (2009). *Landslides 6,* 335–344. *DOI 10.1007/s10346-009-0182-3*, 335–344.
17. 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. *DOI 10.1007/s10346-010-0203-2*, 483–492.
18. Collins, B. D., Kayen, R., & Tanaka, Y. (2012). Spatial distribution of landslides triggered from the 2007 Niigata Chuetsu – Oki Japan Earthquake. *Engineering Geology 127*, 14–26. http://doi.org/10.1016/j.enggeo.2011.12.010
19. Wartman, J., Cox, B., Meneses, J., Moreno, V., & Olcese, M. (2008). Landslides triggered by the 15 August 2007 M8 . 0 Pisco , Peru earthquake, 10. *Earth and Planetary Science Letters*
20. Harp, B. E. L., & Crone, A. J. (2006). Landslides triggered by the October 8, 2005, Pakistan. Earthquake and associated landslide-dammed reservoirs. *Geomorphology 94*, 1-9
21. Kieffer, D. S., Eeri, M., Jibson, R., Eeri, M., Rathje, E. M. et al. (2006). Landslides Triggered by the 2004 Niigata Ken Chuetsu, Japan, Earthquake. *Earthquake Spectra 22 (03)*, 47–73. http://doi.org/10.1193/1.2173021
22. Keefer, D. K., Wartman, J., Navarro, C., Rodriguez-marek, A., & Wieczorek, G. F. (2006). Landslides caused by the M 7. 6 Tecomán, Mexico Earthquake. *Engineering Geology 86*, 183–197. http://doi.org/10.1016/j.enggeo.2006.02.017
23. Bouhadad, Y. (2010). Earthquakes- induced landslides in Algeria : The Laalam, March 20 th, 2006 earthquake. *Earthquake Engineering Center*, *12*, 5–9.
24. 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. http://doi.org/10.1016/j.enggeo. 2006.02.016
25. Jibson, R. W., Harp , E. L., Schulz, W., & Keefer, D. K. (2004). Landslides triggered by the 2002 Denali fault, Alaska, earthquake and the inferred nature of the strong shaking. *Earthquake Spectra 20 (3)*, 669–691.
26. Garc-Rodriguez, M. J. (2010). Assessment of earthquake-triggered landslide susceptibility in El Salvador based on an Artificial Neural Network model. *Natural Hazards and Earth System Science 10*, 1307–1315. http://doi.org/10.5194/nhess-10-1307-2010
27. Khazai, 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. http://doi.org/10.1016/S0013-7952(03)00127-3
28. 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*, 251–270.
29. Meunier, P., Hovius, N., & Haines, A. J. (2007). Regional patterns of earthquake-triggered landslides and their relation to ground motion. *Earth and Planetary Science Letters 34*, 1–5. http://doi.org/10.1029/2007GL031337
30. Keefer, D. K. (2000). Statistical analysis of an earthquake induced landslides distribution — the 1989 Loma Prieta, California event*. Geology Enginnering 58,* 231-249.
31. Kamp, U., & Owen, L. A. (2016). GIS-based landslide susceptibility mapping for the 2005 Kashmir earthquake region, (November 2008). *Geomorphology, 101*, 631-642. http://doi.org/10.1016/j.geomorph.2008.03.003
32. Zaruba, Q., & Mencl, V. (1982). *Landslides and their control.* Elsevier Scientific Publishing Co.
33. Keefer, D. K. (1989). Statistical analysis of an earthquake induced landslides. *Engineering Geology 58, 231-249.*
34. Khazai, B., & Sitar, N. (2004). Evaluation of factors controlling earthquake-induced landslides caused by Chi-Chi earthquake and comparison with the Northridge and Loma Prieta events. *Engineering Geology 71(1-2)*, 79–95. http://doi.org/10.1016/S0013-7952(03)00127-3
35. Wilson, R. C. (1993). *Relation of arias intensity to magnitude and distance in california*. U. S. Geological Survey. Menlo Park, California 94025

36. Chousianitis, K., Del Gaudio, V., Kalogeras, I., & Ganas, A. (2014). Predictive model of Arias intensity and Newmark displacement for regional scale evaluation of earthquake-induced landslide hazard in Greece. *Soil Dynamics and Earthquake Engineering*, *65*, 11–29. http://doi.org/10.1016/j.soildyn.2014.05.009
37. Travasarou, T., Bray, J.B. & Abrahamson, A. (2003). Empirical attenuation relationship for Arias Intensity. *Earthquake Engineering and Structural Dynamics 32*, 1133-1155.
38. Lei, C. I. (2012). Earthquake-Triggered Landslides. *1st Civil and Environmental Engineering Student Conference*, (June), 1–6.
39. Arias, A. (1970). *A measure of earthquake intensity. Seismic Design for Nuclear Power Plant*, ed. R.J. Hansen, MIT Press: Cambridge.
40. Fortunato, C., Martino, S., Prestininzi, A., & Romeo, R. W. (2012). Nuova versione del Catalogo italiano degli Effetti Deformativi Indotti da forti Terremoti (CEDIT) new release of the italian catalogue of earthquake-induced ground failures. *Engineering Geology and Environment 2*, 63–75. http://doi.org/10.4408/IJEGE.2012-02.O-05
41. Johnson, C. W.C, Bürgmann W. R and Pollitz, F. F. (2015). Rare dynamic triggering of remote M≥5.5 earthquakes from global catalog analysis. *Journal of Geophysical Research*: Solid Earth.
42. Meunier, P., Hovius, N., & Haines, J. A. (2008a). Topographic site effects and the location of earthquake induced landslides. *Earth and Planetary Science Letters 275(3-4)*, 221–232. http://doi.org/10.1016/j.epsl.2008.07.020
43. Kıncal, C., Akgün, K. A. M & Koca, Y. (2009). Landslide susceptibility assessment in the Izmir (West Anatolia, Turkey) city center and its near vicinity by the logistic regression method. *Environmental Earth Science 59*, 745-756.
44. Xu, C., Xu, X., Yao, X. & Dai, F. (2014). Three (nearly) complete inventories of landslides triggered by the May 12, 2008 Wenchuan Mw 7.9 earthquake of China and their spatial distribution statistical analysis. *Landslides 11*, 441–461
45. Mahmood, I., Qureshi, S. N., Tariq, S., Atique, L., & Iqbal, M. F. (2015). *Analysis of landslides triggered by October 2005, Kashmir Earthquake* – PLOS Currents Disasters
46. Lin, C.W, Liu, S.H, Lee, S.Y & Lin, C.C (2006). Impacts of the Chi-Chi Earthquake on subsequent raifall-induced landslides in central Taiwan. *Engineering Geology 89 (2)*, 87-101
47. Dai, F.C. & Lee, C.F. (2001). Frequency -volume relation and prediction of raifall-induced landslides. *Engineering Geology 59 (3)*, 253-266.
48. Collins, B.D & Znidarcic D. (2001). Stability Analyses of rainfall-induced landslides. *Geothechnical and Geoenvironmental Engineering 130 (4)*, 362-372.
49. Wang, G.F & Sassa, K. (2003). Pore-pressure generation and movement of rainfall-induced landslides: Effects of grain size and fine particle movement. Engineering Geology 69 (1), 109-125.
50. Chen, H & Lee, C.F. (2003). A dynamic model for rainfall induced landslides on natural slopes. *Geomorphology* 51 (4), 269–288. http://dx.doi.org/10.1016/S0169-555X(02)00224-6.

This page is intentionally left blank