

HIGH MAGNITUDE EARTHQUAKES TRIGGER LANDSLIDES AND FLOODS

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Summary:

The most devastation natural disasters are earthquakes, landslides and floods aside from hurricanes, tornados, volcanic activity, drought etc. It is the interaction of these effects and their mutual cause and effect relationship that are investigated. Earthquake-induced landslides have been the source of significant damage and loss of people and property. These interactions are being investigated thought the world and special attention is given to the earthquakes which happened numerous years ago. Ground shaking due to earthquakes destabilizes cliffs and steep slopes, causing landslides and rockfalls as a significant side-effect. Nearly 60% of all landslide are triggered by earthquakes. Landslides set off by the devastating earthquake in 1949 in Ecuador of $ML=6.8$ proved to be the deadliest feature of the disaster. The landslides also caused some flooding by changing water-flow patterns. Heavy rain and unconsolidated or fractured rock are exacerbating factors. 1970 Peru earthquake $Mw=7.9$ caused a huge rock avalanche that killed almost 54,000 people and buried two cities. Kaikoura earthquake in New Zealand which occurred in 2016 of magnitude $Mw=7.8$ triggered over 80,000 landslides and brought up a reinvestigation of the 1929 Murchison earthquake $Mw=7.3$. This was a major event that probably triggered even more landslides than the most recent earthquake. The shallow quake that occurred in the region of Maca in south Peru, $Mw=6.0$ in July 2013 led to ground subsidence causing numerous landslides and flooding. It has been suggested that there is an analogy between the mechanics of ground movements and tectonic faults, opening up new avenues for research into the dynamics of these faults.

Key words:

Earthquakes, Landslides, Floods, Magnitude, Peak Ground Acceleration, Focal Depth, Landslide Affected Area.

1. INTRODUCTION

Landslides triggered by earthquake actions are seen as secondary effects or as earthquake's result. Usually, landslides are mandatory with earthquakes of high magnitudes. As movement of a huge amount of land can be of several centimeters devastations can be enormous. Due to its hazardous effects, there is a growing interest of different researchers and science community for this complex issue. It is interesting to note that in several occasions, mostly in the mountainous regions, it was the landslides which caused casualties and not the earthquake itself.

The triggering of landslides is controlled by two main families of parameters: (1) the parameters related to the source (magnitude, focal mechanism), and (2) the parameters related to the site (topography, geology, hydrology). New research has grouped these parameters into five main factors.

The well-known Wenchuan earthquake of 12 May 2008, measuring magnitude $M_s = 8.0$ ($M_w = 7.9$), almost 20, 000 fatalities were due to landslides triggered by the shaking [16, 18]. 1970 Ancash earthquake, $M_s = 7.7$ ($M_w = 7.9$), in Peru, was the worst catastrophic natural disaster in the history of Peru [12]. It caused a huge rock avalanche that killed almost 54,000 people and burned two cities. Later in July 2013, Peru was hit by a very shallow earthquake, ($M_w = 6.0$). The Maca landslide 20 km far from this earthquake, was activated, being located outside the region of significant deformation. GPS stations were installed in order to monitor the movement of the landslide [10]. The 2016 Kaikoura earthquake in New Zealand was as well a high magnitude ($M_w = 7.8$) earthquake. It triggered up to 100,000 landslides in Northern Canterbury and southern Marlborough. The database formed by [8], updated by [13] and for New Zealand provide by [3], all specified the magnitude of the earthquake as the dominant factor.

1.1. Generation phenomena

It is believed that the earthquake-triggered landslides are generated by two possible phenomena. One, due to horizontal acceleration there is an increase of shear stress (removal of lateral and underlying support (erosion, previous slides, road cuts and quarries; increase of load (weight of rain/snow, fills, vegetation); increase of lateral pressures (hydraulic pressures, roots, crystallisation, swelling of clay; transitory stresses (earthquakes, vibrations of trucks, machinery, blasting); and regional tilting (geological movements)), and the other is decrease in soil strength (weathering); change in state of consistency; changes in intergranular forces (pore water pressure, solution); and changes in structure (decrease strength in failure plane, fracturing due to unloading). The effects of an earthquake on the landslide and its characteristics depends on the earthquake attitudes (location and magnitude) on one side and on local site conditions on the other side.

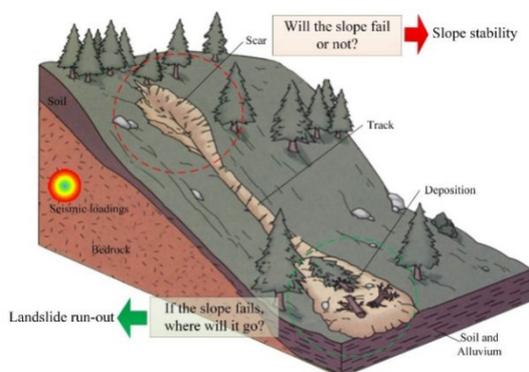


Figure 1. Stability and run-out analysis of earthquake-induced landslides [17]

Until the beginning of the XX century two large database have been compiled regarding earthquake induced landslides [8, 13]. In his detailed analysis Keefer [8], which was based on a dataset of 40 worldwide earthquakes and became a milestone for this research, defined four relationships between earthquake characteristics and landslide distribution. This information was updated by Rodríguez [13] in 1999, and at that time 76 earthquakes and connected landslides were elaborated. It is the magnitude of the earthquake which is firstly investigated and then interconnected with different landslide characteristics. All the proposed equations are magnitude dependent either directly or indirectly.

1.2. Main characterizes of earthquake induces landslides

The four relationships defined by [8] and some updated later on by [13] are presented below.

1.2.1. Minimum earthquake magnitude required to generate various landslide types

Depending on the type of a landslide the minimum magnitude was defined. The smallest local earthquake in Keefer's study that triggered rock falls, rock slides, soil falls, and disrupted soil slides had a magnitude of $M_L = 4.0$; ~ 4.5 for soil slumps and soil block slides; ~ 5.0 for soil lateral spreads, rapid soil flows, subaqueous landslides, rock slumps, rock block slides, and slow earth flows; ~ 6.0 for rock avalanches; and ~ 6.5 for soil avalanches. Additionally, [8] noted the possibility that landslides of all types could occasionally occur in earthquakes smaller than those indicated as they can also be triggered by nonseismic agents.

However, new investigations and observations have indicated that fatal landslides can be and are triggered by even smaller earthquakes, e.g. earthquake of magnitude $M=2.9$ in China in 1984, when a failure of an aeolian deposit cliff with a slope of $50-60^\circ$ in Qinghai was observed. It was suggested by [2] that this was caused by the shallow earthquake source. In this case the focal depth, which is neglected for the large magnitude crustal earthquakes, as it is of little significance in terms of the proximity of the source of energy release to the ground surface [14], will control the intensity of shaking in the epicentral area. This is quite acceptable and possible as a landslide may occur depending the slopes instability, so a very weak shaking and a rather small PGA may trigger a landslide.

It is interesting to note that the first information on the earthquake in Greenland on June 17, 2017 of a magnitude of $M=4.1$ which was believed that it had triggered a fatal landslide was denied after detail research took place. At first Prof. Nettles stated "The $M=4.1$ earthquake does not explain the large, long-period (slow) seismic signal detected by seismometers around the globe. The long-period signal appears to be due to a landslide, and the time of the long-period signal is later than the time of the high-frequency (earthquake) signal. It is possible the earthquake triggered the landslide." What this means is that both the earthquake and landslide generated seismic signals, but that the earthquake signal appeared first, suggesting the quake triggered the slide. During the research scientist have determined that landslide was so large that it generated significant seismic energy. It is exactly from the signals that the clues were revealed and that is the duration and characteristic of the seismic signals. Not only did the seismic waves last for approximately five minutes, but they were monochromatic and slowly increased in amplitude (the highest amplitude waves lasted about 30 seconds). Such traits are "indicative of complex landslide signals." [6]. This is another issue which proves the complexity of such research and investigations.

1.2.2. Area affected by the landslide as a function of the earthquake magnitude

The first formula (1) was proposed by [8] and updated by [13] in 1999

$$\text{Log}_{10}(\text{Area affected}) = \text{Magnitude} - 3.46(\pm 0.47) \quad (1)$$

Landslides in New Zealand were investigated by [3,4] and another formulation (2) in respect to the magnitude was obtained.

$$\text{Log}_{10}(\text{Area affected}) = 0.96(\pm 0.16)\text{Magnitude} - 3.70(\pm 1.1) \quad (2)$$

The landslide affected areas were smaller in respect to the ones obtained for the world scale, Keefer (1984), most probably due to the limited range of geologic environments.

In 2017 [15] compared the relations given by [8] and [13] as presented in Figure 2. The upper limit defined by [13] included all the earthquakes, except one.

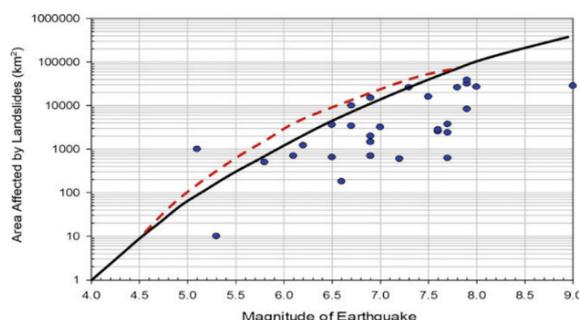


Figure 2. Relationship between the total landslide affected area by the earthquake and the magnitude of the earthquake - solid line Keefer [8], dashed line Rodriguez et al. [13], Tiwari and Ajmera [15]

1.2.3. The maximum distance of landslides from the epicenter (the fault rapture) as a function of the earthquake magnitude

The earthquake magnitude is as well interconnected with the maximum distance of landslides from the epicenter (Figure 3a) and from the fault repute (Figure 3b) as defined in [8]. Magnitudes used in determining upper bounds were typically moment magnitude (M) for $M \geq 7.5$ and Richter surface-wave magnitude (MS) for $M < 7.5$. The landslides were categorized as disrupted landslides, coherent landslides and lateral spreads and flows.

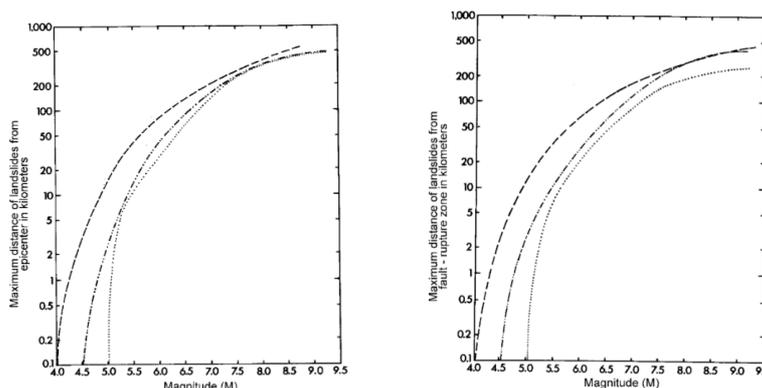


Figure 3. (a) Approximate upper bounds for maximum epicentral distances of landslide in three major categories related to earthquake magnitude, (b) Approximate upper bounds for maximum distances of landslide in three major categories from fault-rapture zones related to earthquake magnitude [8]

Dashed line is upper bound for disrupted landslides, dot-dash line is upper bound for coherent landslides, and dotted line is upper bound for lateral spreads and flows.

1.2.4. Minimum shaking intensity required for landslides to be triggered, as a function of Modified Mercalli Intensity (MMI)

Minimum intensity as per [8] was IV and as per [13] was V. Different intensities were connected to different types of landslides being distributed, coherent or lateral spread and (or) flows. However, when referring to intensity in any means one needs to take care as this is a rather subjective.

1.2.5. Additional introduction of the 3D graphs (magnitude Ms vs Focal Depth and Landslide affected area)

As it has been seen there are several features that affect earthquake triggering of landslides. It is evident that in respect to the type of the soil even smaller magnitude, but with a shallow focal depth can cause significant area movement and enormous devastation, not to mention climatic effects as an additional matter. Here the data obtained by [13], except for the Nepal earthquake, are presented in Figure 4.

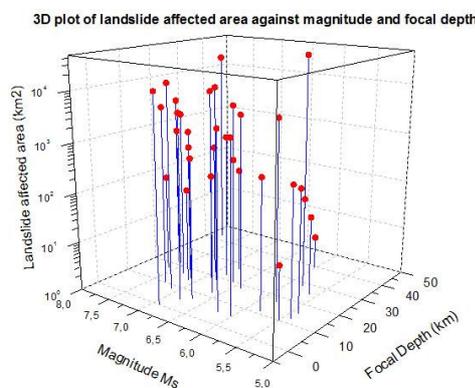


Figure 4. 3D plot of landslide affected area against magnitude and focal depth

In this 3D plot magnitude Ms vs focal depth (km) and landslide affected area (km^2) is illustrated. It is evident that the magnitude is the main factor together with the low focal depth. This is in consistency with the results obtained by [11]. An enormous amount of landslide affected area was realized after the 1988 Sequenay earthquake in Canada,

which has to be investigated in detail and include the new factors that are presented in the Chapter 3. Additionally, it would be interesting to make this interconnection with the peak ground acceleration, which will be the next step in the research and which is presented in the following chapter.

2. INTRODUCTION OF PEAK GROUND ACCELERATION (PGA)

In the recent work by [15] the Peak Ground Acceleration (PGA) as a dominant factor in the earthquake induced landslides was introduced. In this means the landslide area affected by the landslides and the number of landslide as a function of the PGA was connected.

2.1.1. Area affected by the landslide as a function of maximum peak ground acceleration

The upper bound of the relationship between the total landslide area affected by the earthquake-induced landslides and the peak ground acceleration is presented in Figure 5. The maximum area affected by landslides as seen from Figure 5 is within the range of 0.5 to 1.2g. This is a very general illustration as [8] and [13] indicated that in this respect seismological, geological factors and geographic characteristics of the area affected have not been taken into account which will have a substantial influence on the types and number of landslides induced by the earthquake.

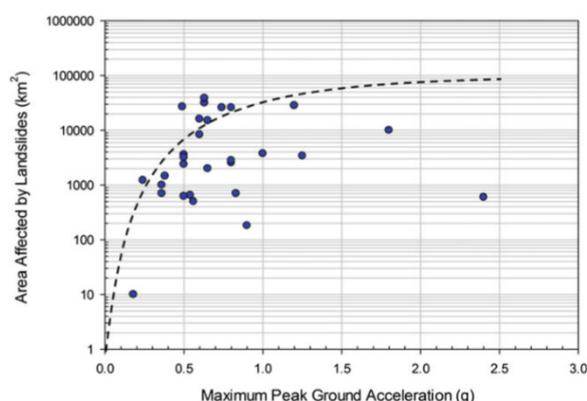


Figure 5. Relationship between the total area affected by the earthquake-induced landslides and the peak ground acceleration [15]

2.1.2. Maximum peak ground acceleration and number of earthquakes

The relationships between the peak ground acceleration and the total number of earthquake-induced landslides observed was firstly done by [15]. The data process by [15] was for landslides of 100 m^2 . They have separated moderate to large scale landslides and all landslides. An evident increase in the number of landslides triggered with an increase in the magnitude of the earthquake when considering is observed. However, a clear relationship between the number of landslides and magnitude could not be made. On the other hand, relationship between the peak ground acceleration and the number of landslides gave better illustrations. On the basis of the developed data as indicated in Figure 6 relationships were made between PGA and the number of moderate to large scale landslides (Eq. 3) and with the total number of landslides of any size (Eq. 4) triggered by the earthquake. Good correlation is observed with smaller amount of scatter[15].

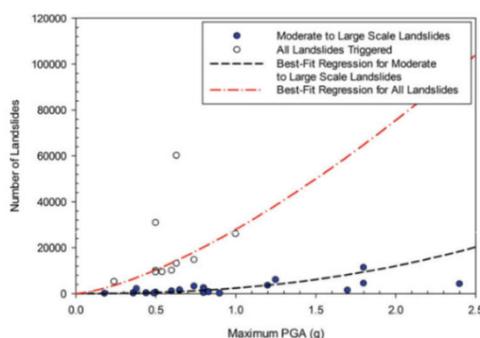


Figure 6. Relationship between the number of landslides triggered and the peak ground acceleration; Open circles represent points in the database that considered all landslides, while close circles represent points in the database that considered only moderate to large scale landslides [15]

For moderate to large scale landslides the relationship reads:

$$N = 2223.2(PGA)^{2.13} \quad (3)$$

While for the total number of landslides of any size triggered by the earthquake:

$$N = 26,967(PGA)^{1.41} \quad (4)$$

It is the peak ground acceleration that directly impacts the stability of a slope subjected to dynamic loading [1]. In this respect, it is acceptable to state that peak ground acceleration in deriving relationships should be preferred over the magnitude of the earthquake.

Data taken from [15] was analyzed in the sense of three factors: magnitude, focal depth and landslide area affected on one hand, and on the other, the magnitude was replaced by the PGA. Only the data with all the available information was analyzed. This means in total 24 earthquakes were elaborated. Figure 7 presents the 3D graphs. It is evident that the majority of the landslide affected areas are located in the range 0.5g to 1.2g while the focal depth is ≤ 40 km, with one case with the focal depth > 40 km. This is in consistency with the analysis obtained by [11]. Representation of the PGA together with the focal depth and landslide area affected is well represented and contains less scatter than the relationship obtained with the magnitude of the earthquakes. It is now a question of the research community dealing with this matter to incorporate PGA as preferable representation or maybe not.

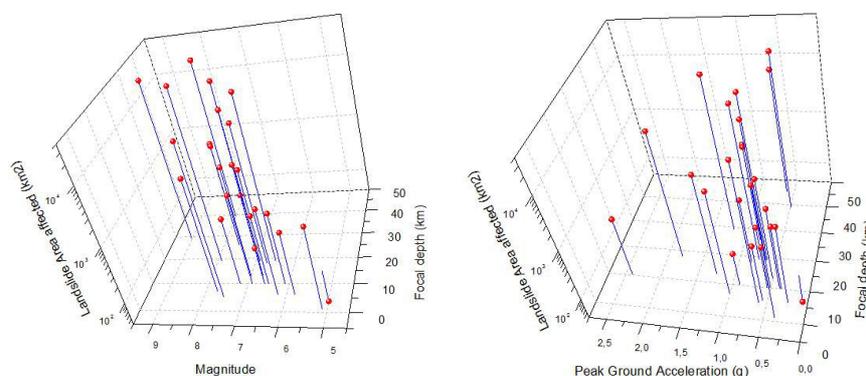


Figure 7. (a) 3D plot of landslide affected area against magnitude and focal depth (b) 3D plot of landslide affected area against PGA and focal depth

3. NEW INVESTIGATIONS

An interesting feature of the high magnitude (or better to refer to PGA) earthquakes are the case of distant triggering of the landslides. In the last two decades, much effort has been invested in studying this phenomenon, and several researchers have compiled worldwide, country or regional databases. The key role in the occurrence of far field landslides may be the susceptibility of slopes prior to earthquake occurrence. This is a topic that has been investigated by only a few researchers. During the analysis, it was noted that most of these landslides are triggered by earthquakes having very deep hypocenters.

Additionally, climatic conditions especially 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. Rain may be very effective in contributing to triggering far field landslides of any typology. For events of equal magnitude, disrupted landslide type outliers may occur further away than those of the coherent landslide type. It is arguable that rainfall-induced and earthquake-induced landslide hazard should be assessed simultaneously, and there is at least one method that combines both of these triggering mechanisms (intensity of rainfall and seismic intensity) in an index related to the landslide hazard potential [7].

Most earthquake-triggered landslide inventories only include rapid landslides, that occur over periods of seconds to minutes. These datasets do not include slow-moving landslides accelerated by earthquakes, and thus do not capture all earthquake-related landslide activity. This is an open research field for many scientists of different disciplines and their mutual interconnection and exchange of knowledge and experience is required.

Researcher Havenith H-B., Torgoev A., Braun A., Schlögel R., and Micu M. [5] gave a new classification of the earthquake-induced landslide event sizes based on seismotectonic, topographic, climatic and geologic factors as presented in Table 1.

Table 1 - Main Factors contributing to earthquake-triggered landslide events [5]

	Inputs	Assessment	Weight
Intensity I	M, D	Arias Intensity AI computed according to Eqs. 1 and 2	AI > 1: I = \sqrt{AI} IF AI ≤ 1: I = AI
Fault factor F	Location, type and length of activated fault	FLF: Location with respect to mountain range MR FT: Fault type mechanism FL: Fault length	a) Fault inside MR: FLF = 2 Near MR: FLF = 1.5; outside MR: FLF = 1 b) Dip-slip fault: FT = 1.5; Strike-slip: FT = 1 c) Fault length ≥ 100 km: FL = 2 Fault length between 20 and 100 km: FL = 1 Fault length < 20 km: FL = 0.5 F = FLF*FT*FL; Range F: 0.5-6
Topographic energy TE	Google Earth analysis	Maximum altitude difference A_{dif} over 100 km ² tested for sample areas in affected zones.	Adif > 1500 m : TE = 4 1000 < A_{dif} ≤ 1500 m : TE = 3 500 < A_{dif} ≤ 1000 m : TE = 2 A_{dif} ≤ 500 m (but hilly): TE = 1 Flat with bluffs: TE = 0.5
Climatic background CB	Climatic information extracted from any published sources	Qualitative estimate considering -antecedent rainfall AR -general climatic conditions (CC: arid – wet climate)	Proved AR=yes and/or CC wet: CB = 2 General conditions (or if not known): CB = 1 Arid climate: CB = 0.5 Very arid climate: CB = 0.2
Lithological factor LF	Published geological information	Qualitative estimate considering the presence of Quaternary (Q) or Tertiary (T) layers and bedrock	Extensive cover of Q-layers: LF = 4 Wide presence of T-layers: LF = 2 Other cases or not known: LF = 1

M magnitude (Mw or Ms as provided in publication), D hypocentral depth as provided

As in all researches until now, the major importance is given to the Intensity (I), meaning to the magnitude and the hypocentral depth of the earthquake, giving the Arias Intensity (AI) as defined by [9]. So, in this respect the dissipated energy is taken into account. Topographic energy (TE) covers the maximum altitude difference. Lithological factor (LF) is something that is rather variable over tens of thousands of square kilometers. The structure of the subsoil can induce strong amplification of the seismic motion (existence of thick cover of loess, sensitive clays and soils of volcanic origin). As seen in numerous previous earthquake induced landslides the influence of climate can have a significant impact. Season of the earthquake occurrence and the existence or nonexistence of rainfall is covered by the Climatic background (CB). Higher landslide susceptibility is observed in the rainy season as it reduces the static slope stability or favor induced seismic ground effects related to the increased pore water pressure as example liquefaction.

A very illustrative representation is given in the Figure 8 of 50 earthquake events that are likely to have triggered most of the landslides – according to the of database [5].The left graph indicates the relative weight of the five contributing factors presented in Table 1. The graph on the right-hand side shows the size of an event in terms of observed and predicted number of induced landslides (resp., red and black squares along the grey horizontal bar produced for each event) and total affected area (blue cross in the same line).

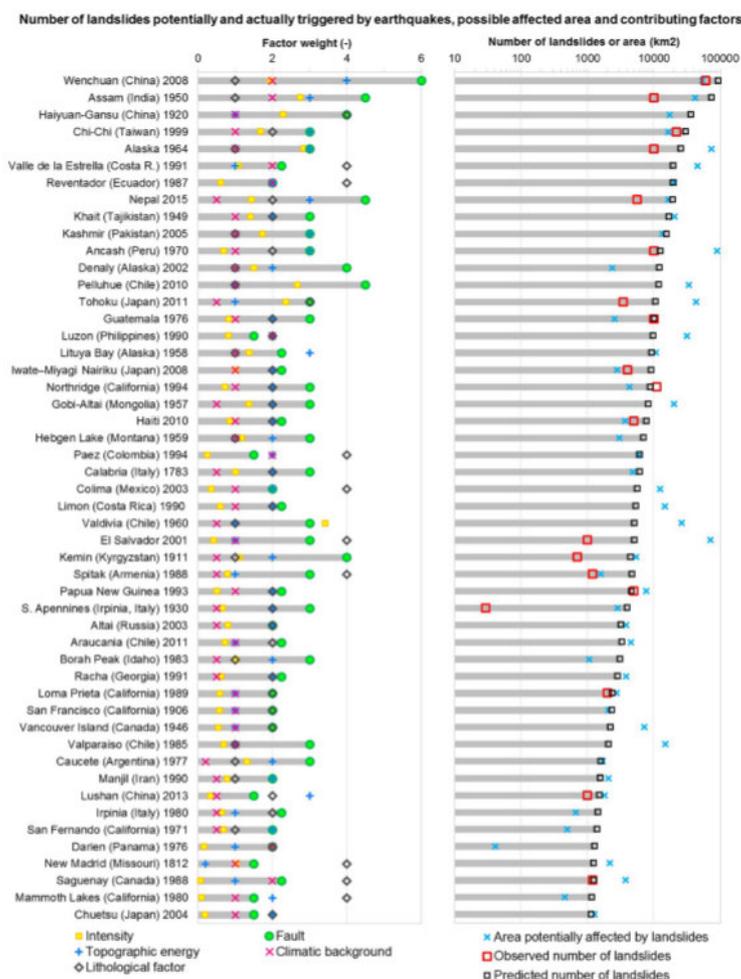


Figure 8. Graphs (events along Y-axis) showing the results of the classification for 50 earthquake events that are likely to have triggered most of the landslides – according to database of [5]

The earthquake which occurred in the region of Maca in Peru in July 2013 opened a new research phase in this field. Previously GPS measurements were installed and on the basis of the obtained and processed data an analogy between the mechanics of ground movement and tectonic faults opening new avenues for research into the dynamics of faults. During the measurements, it was evident that the response of the landslide was both concomitant with the earthquake but also post-seismic. In this respect, slow-moving landslides could be considered as a mechanical analogous of creeping faults [10]. Meaning similarities between the mechanics of the landslides and those of creeping tectonic faults were obtained.

4. CONCLUSION

It is clear that still the magnitude of the earthquake is taken as the major factor in the analysis of the earthquake triggered landslides. It is an effective way as this data is provided by different earthquake centers and the data is easily obtained. Additionally, new features are included besides the ones defined by [8] and their interrelations are investigated through observed events. This is all done with the goal to improve the total seismic hazard assessment especially in the mountain regions. The weighting factors are subjective as they are based on the experience of the scientists which in some cases can be rather misleading. Objective weighting would be more than appreciated, however level of subjectivity will always have to be present in these unpredictable and highly uncertain events. A 3D plot magnitude vs focal depth and landslide affected area regarding the data obtained by [13] was presented and showed the same sequence of behavior as obtained in the [8] data. It is indicative that the 3D illustration of the landslide affected area and focal depth in respect to the PGA is better represented, with a smaller amount of scatter, in respect to the magnitude. It would be useful and interesting to make a data base of earthquakes having small focal depth and its PGA and make connection with the occurrence or non-occurrence of landslides. However, it is a question is it acceptable for the research community to replace the magnitude with the PGA or add the interdependency of the main factors with the PGA as well. The paths of continuous and new research in this filed are still ongoing and one of them was stated after

the installation of the GPS measurements in Peru which revealed possible similarities between the mechanics of the landslides and those of creeping tectonic faults.

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