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Landslide inventory of the 2010 Mw 8.8 Maule earthquake, Central Chile.

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Abstract

Landslides are a major source of fatalities and damage during strong earthquakes in mountain areas. Detailed, comprehensive inventories of landslides triggered by earthquakes are essential parts of seismic landslide hazard analyses. Chile being such a seismic country, there are not complete landslide inventories induced by subduction earthquake in Chile. An exceptional case study from which is possible to make a thorough study of the occurrence of landslides generated by earthquakes in a subduction margin, is the 27/02/2010, Mw 8.8 earthquake in central- southern Chile.

From the analysis of satellite images and bibliographic information, a preliminary inventory of landslides generated by the earthquake was conducted by Escobar (2013) and Moya (2015), between the regions of Valparaiso and the Araucanía, focused on the Coastal Cordillera and coastal plains. This paper is aimed at complete the inventory adding earthquake-induced landslides in the Main Cordillera between 32.8 ° and 38.5 ° S. The new mapped landslides (>30 m^2 surface area) were identified by interpretation of satellite images.

The full inventory shows over 1160 events in total, including rock falls, rock and soil slides, flows and lateral spreads among others. The maximum distance to the epicenter is 487 km. Most of the landslides (over 800) are located in Principal Cordillera. The review of the data shows that the events are not evenly distributed in the study area, with the presence of several clusters of landslides, the most important of those located in the Arauco Peninsula, Bio Bio region. Landslides show not clear correlation with seismic intensity.

By comparing the number of landslides triggered by the Maule earthquake with other earthquakes (Tohoku, Chi-chi, Wenchuan, Kasmir), we note that the number of landslides generated by subduction earthquakes is lower than events triggered by shallow crustal earthquakes (at least an order of magnitude), which is very important to consider in future seismic landslide hazard analysis.

Keywords: landslide, Chile, earthquake.

1. Introduction

Landslides are a major source of fatalities and damage during strong earthquakes in mountain areas. Detailed, comprehensive inventories of landslides triggered by earthquakes are essential parts of seismic landslide hazard analyses. In such cases, the landslide distribution, the topography, the geology and the ground shaking can be compared and analyzed on Geographic Information Systems (GIS) platforms to produce landslide susceptibility and hazard analyses for the affected region. Without a highly accurate, complete landslide inventory, such analyses cannot be fully accomplished. Even though Chile is frequently affected by large subduction earthquakes, there are no inventories of landslides induced by subduction earthquakes. The only full inventory is that from the Mw 6.2, shallow crustal Aysén earthquake in 2007 ([1], [2]).

Therefore, the 2010 Mw 8.8 Maule earthquake give us an extraordinary opportunity to produce a landslide inventory and to understand the distribution and controls for the generation of landslides triggered by large subduction earthquakes in Chile. With bibliographic compilation and interpretation of satellite images, we generated a complete inventory of landslides triggered by the Maule earthquake between 32.5° and 38.5° latitude S. We mapped 1160 landslides related to Maule earthquake from a total area of about 120,500 km^2, from which we can obtain important inputs to consider in future seismic landslide hazard analysis.

2. The Mw 8.8 Maule earthquake

Chile has a noticeable tectonic and geomorphological context. The Andes in northern and central parts of the country can be reasonably divided into three main north– south trending morphostructural zones. The westernmost zone is the Coastal Cordillera, consisting predominantly of Late Paleozoic and Mesozoic igneous rocks, with paired belts of Paleozoic metamorphic rocks cropping out south of Pichilemu (34ºS). The central depression, or Central Valley, is a depression with a Mesozoic to Quaternary sedimentary infill [3]; south of Santiago, this is the main agricultural zone and contains several major cities. The easternmost zone is the Principal or Main Cordillera, a chain of high mountains that in its western part in Chilean territory comprises Oligocene–Miocene continental volcaniclastic rocks, intruded by Miocene–Pliocene granitoids [3].

Overall, the geological evolution of Chile has resulted from the effects of east-directed subduction of Pacific (and proto-Pacific) ocean floor beneath the South American continent. This subduction is the force that generated the Andes, which primary uplift dates back to a Miocene event, but whose emergence continues today, as exemplified by major earthquake activity [3]. Their elevation is accompanied by significant crustal shortening, principally accommodated by eastward thrusting. Subduction is also evidenced by an almost continuous line of active and dormant volcanoes, mostly andesitic stratovolcanoes, which are almost along the entire length of the country.

The earthquake occurred on 27 February 2010 is an example of the subduction activity. Known as the Maule earthquake, it is the sixth largest recorded by the United States Geological Survey (USGS) and is the second greatest in the country after the 1960 Valdivia earthquake. However, this is the largest event ever recorded instrumentally in Chile [3].

The rupture zone of this earthquake matches with a seismic gap, where a great earthquake has not occurred since 1835 and that different authors ([4], [5], [6]) from GPS receivers installed in the 90s (which measured a shift eastward terrain up to 4 cm / year [7]) considered that was ripe and with a high probability of generating an earthquake in the near future.

This earthquake was located along the subduction of the Nazca plate beneath the South American plate, for which the convergence rate is close to 6.6 cm/y. The rupture zone had about 450 km along the Chilean coast and 160 km from east to west [8]. The hypocenter was located at the geographic coordinates 36°17'23"S - 73°14'20"W with a depth of 37 km according to the National Seismological Service.

Thirty-five accelerometers took measurements that night, with records that reached up to 0.93 g (horizontal component) and 0.70 g (vertical component) [9] and one station recorded 1.25 g before saturating [10].

The great Chilean interplate or thrust earthquakes are characterized by a few zones of highest slip that controlled their rupture [11], which are called asperities, following the original idea of Kanamori and Stewart (1978). The rupture process of the Maule earthquake was characterized by more than one asperity ([12], [13], [14], [15]); however, the asperity with higher slip (main asperity) is located in the northern part of the seismic gap, approximately in the same rupture area of the 1928 Talca earthquake [16].

The largest aftershock occurred on January 2, 2011, Mw 7.2, 24 km of focal depth and PGA between 0.08-0.32 g, while on March 11, 2010 occurred the largest events (Mw 6.9 and 7.0) of a series of shocks of normal focal mechanism with 10-25 km depth and PGA values up to 0.24 g (USGS catalogue). The normal shocks were attributed to the reactivation of a crustal fault due the high Coulomb stress change produced by the Maule earthquake in subsurface fluids [17].

According to studies by [18] for an earthquake like the Maule earthquake, a number of landslides around 50,000 would be expected. However, a revision carried out after the 2010 earthquake allowed checking that this figure was far from being reached.

3. Landslides Inventory

Escobar (2013, [19]) started the inventory of landslides generated by the Maule earthquake from the analysis of satellite images and bibliographic information between the regions of Valparaiso and the Araucanía, focused on the Andes Coastal Cordillera and coastal plains, the area closest to the rupture. This inventory has been complemented by [20] in the Arauco peninsula, and this work in the Principal Cordillera, being the Chile-Argentina border limit the eastern boundary for mapping. This paper is aimed to present a comprehensive inventory of landslides induced by the 2010 earthquake between 32.5 ° and 38.5 ° latitude S.

For the bibliographic compilation, we collected information about the previously recorded landslides events triggered by the Maule earthquake. We reviewed 107 technical reports of the National Geological and Mining Survey of Chile (SERNAGEOMIN) related to the earthquake. From these reports, we extracted the relevant information related with landslides and lateral spreads and we excluded infrastructure damage, as well as the risk of flooding and cracking. We also reviewed the georeferenced reports of road interruption problems caused by the earthquake, done by the Ministry of Public Works and we incorporate the inventory of lateral spreads provided by [21], and the inventory of landslides in the coastal fringe of the Biobio administrative region provided by [22].

The landslides were mapped by interpreting Landsat satellite images before and after the earthquake with the Google Earth tool. A visual inspection of these strips was done at an eye height of ~1-2 km, decreasing the height when an alteration was detected in the vegetation, or when bare spots or typical mass movement morphologies were present [23]. We visually inspect the earliest available images after the earthquake, mapping between the 1:2000 and 1:10,000 scales. Once a landslide was identified, the location was compared with the latest pre-seismic image without cloud or snow cover. Validation field trips were done in the coastal regions with the higher densities of landslides in order to identify, classify and describe the previously mapped landslides by failure mode. Field inspections allowed us to add a number of small mass movements that were not recognized on the satellite images.

In total we mapped 1160 landslides (Fig. 1), including rock falls, rock and soil slides, flows and lateral spreads, among others. The maximum distance to the epicenter is 487 km. The total area mapped is nearly 120,500 km^2.

Most of the landslides (over 800, mainly disrupted shallow slides and falls) are located in Principal Cordillera, which is explained by the geomorphological differences between the Coastal Cordillera and Principal Cordillera, the latter with a stronger relief and steeper slopes. There are some landslides located in the central depression, which are mainly lateral spreads caused by soil liquefaction, according to the bibliographic review.

Fig. 1 shows landslides and the seismic intensities of the 2010 Maule earthquake, isoseismals extracted from [24]. Fig 2 exhibits the amount of landslides between each isoseismal. Very few landslides (34) are in the area of higher intensity (VIII) while most of them (800) are in the area of lower intensities ($\leq$V). We can conclude there are not positive correlation between landslides and intensity. We are working on the correlation with other relevant parameters such as landslide size, relief, geology, PGA and dominant frequency from strong ground motion records, etc. to interpret the genesis of the landslides.

Fig. 2 shows the histogram of landslides with a minimum size of 30 m^2 and a maximum of 230,371 m^2. An important number of landslides (387) are in the range of 1000 m^2 to 5000 m^2. Very few landslides (29) have more than 50,000 m^2. Most of landslides that we collected by bibliographic compilation, located in Coastal Cordillera and corresponding to minor rock falls and slides along roads do not have record of their size; in such cases we assigned to them an estimated value of 100 m^2.

The events are not evenly distributed in the study area. We highlight the formation of clusters of landslides (Rio Claro, Linares, Laguna El Maule, Pinto, Concepcion, Arauco Peninsula). The most important (127) of those is located in the Arauco Peninsula, Bio Bio region (Fig. 1), mainly triggered in low strength Neogene sedimentary rocks, suggesting an important lithologic control as a major factor in the generation of landslides [20].

We compared the dataset with curves by [25] and [26] of maximum landslide area and epicentral distance (Fig. 3). The figure about maximum landslide area shows that landsliding fit well beneath the upper bounding curves proposed [25] and [26] from statistical records of worldwide earthquake-induced landslides (Fig. 3 left). On the other hand, the figure associated to maximum epicentral distance for disrupted landslides exhibit that the Maule earthquake is almost at the upper limit of the curve (Fig. 3 right). We can conclude the landslide geographical distribution is within the expected for a M 8.8 earthquake in a mountainous environment.

The 2008 Wenchuan earthquake (Mw 8.3, cortical earthquake) generated more than 60,000 individual landslide scarps in a very extensive area covering around 35,000 km^2 [27]; the 1994 Northridge earthquake (Mw 6.7, cortical earthquake) triggered around 11,000 landslides [28]; the 1999 Chi Chi earthquake (Mw 7.6, cortical earthquake) caused 22,000 landslides (of which 9,272 larger than 625 m2) [29]; and the 2005 Kashmir earthquake (Mw=7.6, cortical earthquake) caused only 2400 landslides [30]. On the other hand, we have the 2011 Tohoku earthquake (Mw 9.0, subduction earthquake), the strongest one known to have hit Japan, for which [31] provide a high-quality geospatial database of 3477 individually mapped and classified landslides from a 28,380 km^2 area of northeast Japan; and the Maule earthquake (Mw 8,8, 2010, subduction earthquake), the second greatest recorded in Chile, for which we mapped 1160 landslides in an area of 120,500 km2 aprox.

From the above, it is evident the difference in the number of landslides that generates a cortical earthquake versus a subduction earthquake. The latter tend to trigger a much smaller number of landslides compared to those generated by cortical earthquakes, about at least an order of magnitude. This conclusion is very important to consider in future seismic landslide hazard analysis.

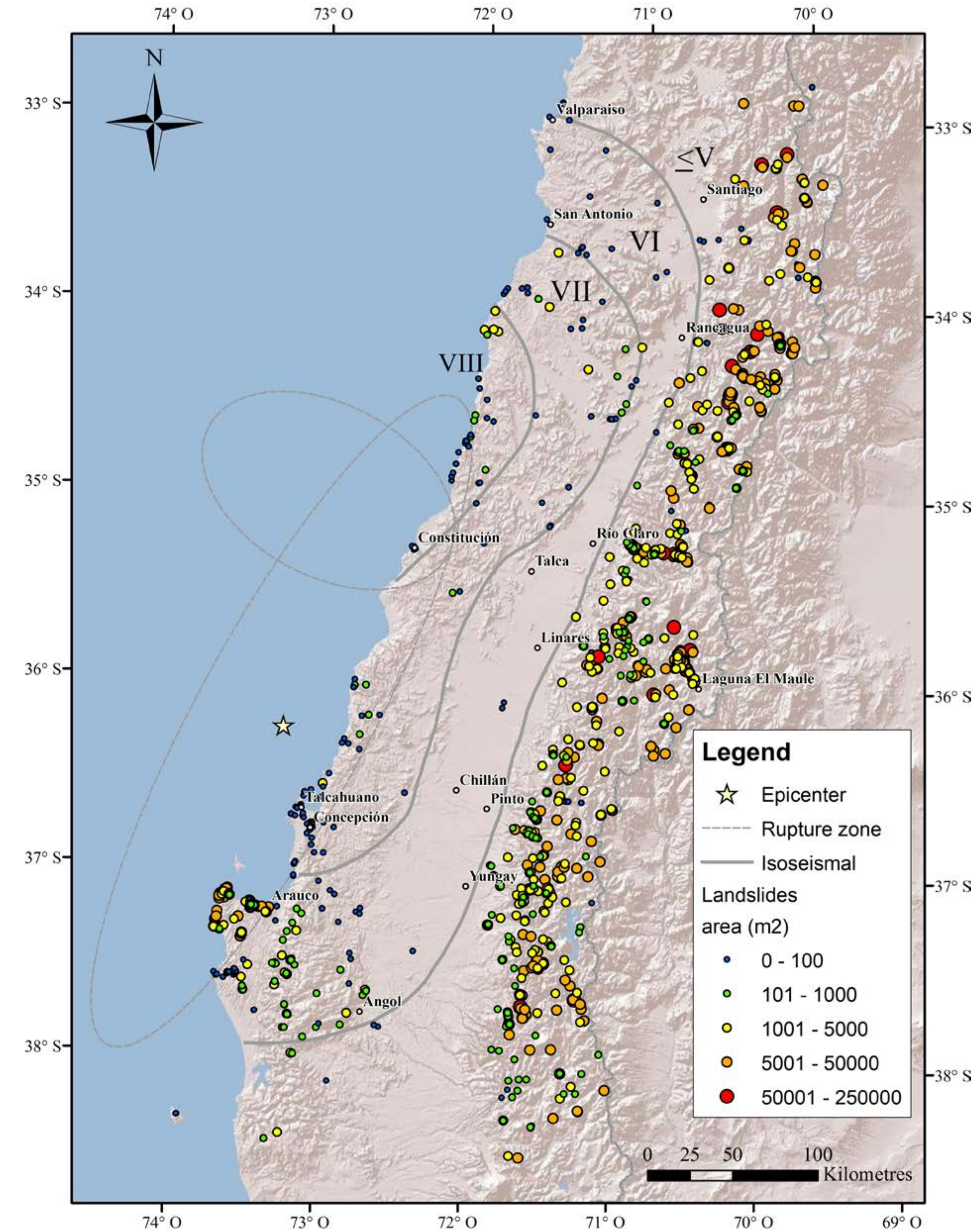


Fig. 1 – Map with location and areas of landslides generated by 2010 Maule earthquake and intensity. Rupture zone extract of [16]. The epicenter was located according to the National Seismological Service. Isoseismal extracted from [24].

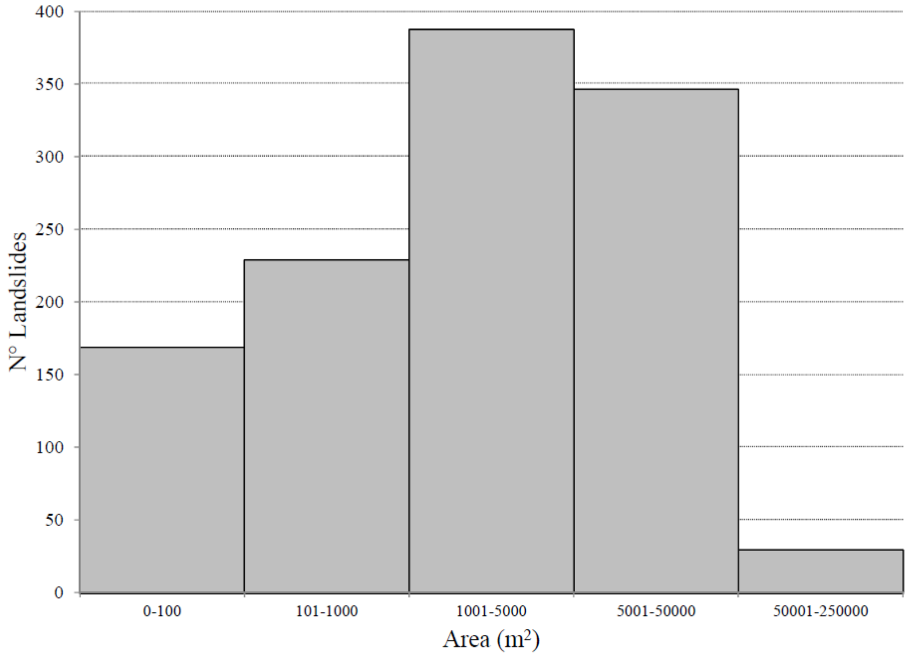


Fig. 2a - Number of landslides by area.

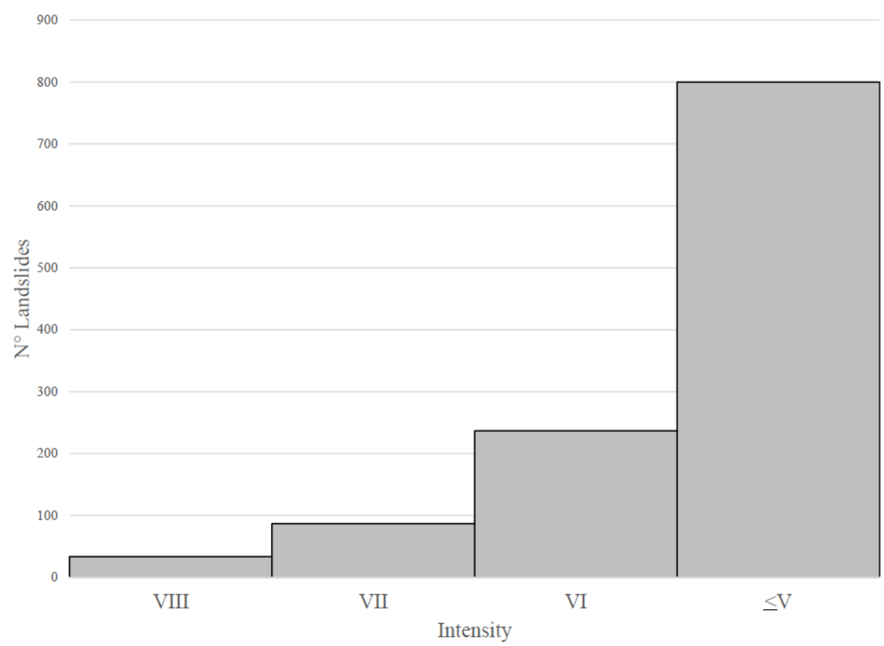
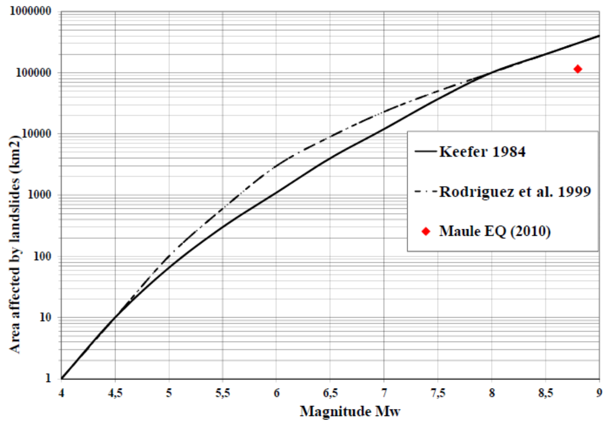


Fig. 2b - Amount of landslides between each isoseismal.



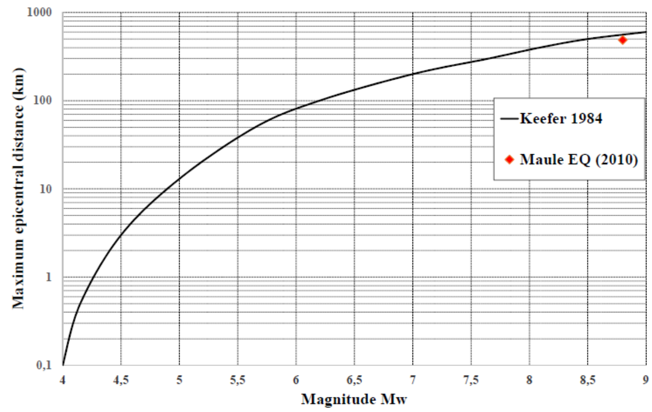


Fig. 3 - Comparison with curves of [25] and [26] of maximum landslide area and epicentral distance for worldwide earthquake-triggered landslides. Left. Maximum landslide area. Right. Maximum epicentral distance for disrupted landslides.

4. Conclusions

The 2010 Mw 8.8 Maule earthquake triggered 1160 landslides, including rock falls, rock and soil slides, flows and lateral spreads, among others. Most of the landslides (over 800) are located in Principal Cordillera, the area with stronger relief but where lower intensities where registered. The landslide tended to occur in clusters, the most important of those located in the Arauco Peninsula, Bio Bio region. Ongoing research is aiming to find relationships between landslide size and distribution with geomorphological, geological and strong ground motion parameters.

We compared the dataset with curves from literature of maximum landslide area and epicentral distance and we conclude the landslide geographical distribution is within the expected for a M 8.8 earthquake in a mountainous environment.

By comparing the number of landslides triggered by the Maule earthquake with other recent earthquakes, we note that the number of landslides generated by subduction earthquakes is lower than events triggered by shallow crustal earthquakes (at least an order of magnitude), which is very important to consider in future seismic landslide hazard analysis.

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