A web-GIS database of the scientific articles on earthquake-triggered landslides

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Abstract. Over the last two decades, the topic of earthquake-triggered landslides (EQTLs) has shown an increasing relevance in the scientific community. This interest is confirmed by the numerous articles published in the international, peer-reviewed journals. In this work we present a database containing a selection of articles published on this topic from 1984 to 2021. The articles were selected through a systematic search on the Clarivate analytics' Web of Science-Core Collection™ online platform and were catalogued into a web-GIS, which was specifically designed to show different types of information. After a general analysis of the database, for each article were identified the bibliometric information (e.g., author(s), title, publication year), the relevant topic/sub-topic category(s) and the addressed earthquake(s). The analysis allowed to infer general information and statistics on EQTLs (e.g., relevant methodological approaches over time and in relation to the scale of investigation, most-studied events), which can be useful to get a spatial distribution of the articles and a general overview of the topic.

1 Introduction

Earthquakes are one of the most threatening and devastating natural hazards worldwide, which cause significant losses of life and damages to human structures and infrastructures. Although most of the damage is related to the partial or full collapse of buildings caused by ground shaking, in many cases other ground effects (e.g., tsunamis, liquefaction, landslides) can significantly increase the impact of the seismic event (e.g., Jibson and Harp, 2012). In particular, earthquake-triggered/coseismic landslides (EQTLs) are responsible for approximately 70% of all earthquake-related fatalities not directly caused by ground shaking (Marano et al., 2010). Casualties caused by EQTLs are generally related to the collapse of buildings induced by the down-slope movements, which frequently tends to cover up previous structural damage due to the seismic shaking (Bird and Bommer, 2004). EQTLs often interrupt road networks and other transportation infrastructures, hampering rescue, supply, and recovery activities (Allstadt et al., 2022). EQTLs can also partly or completely block river channels, inducing downstream floods (e.g., Fan et al., 2012) and, in the long-term, causing changes of the drainage-basin characteristics (Keefer, 1999). For all these reasons, EQTLs are an important component of natural hazard assessment in seismically active

areas, and in recent years the study of collateral seismic hazards is becoming an issue of increasing relevance (Wasowski et al., 2011), also in the framework of multi-risk assessments, accounting for potential cascading effects.

In this article we describe the results of a systematic search of scientific papers concerning EQTLs, published in peer-reviewed international journals in the past decades. Searching on the Clarivate analytics' Web of Science-Core Collection™ online platform, we have collected 810 articles which were organized in a specific web-GIS database for the analysis. The identified articles deal with EQTLs theme from numerous points of view, focusing on a wide range of aspects, such as spatial distribution in relation to earthquake location, triggering and propagation mechanisms, impact on human activities. The aim of this work is to provide a tool which shows the geographical distribution of the articles published on this topic classified using different types of information, which may represent a starting point for future analyses. The manuscript is organized as follows: section 2 describes the structure of the database; section 3 discusses the type of information addressed by the articles and section 4 summarizes some main conclusions.

2 Data and structure of the literature database

The EQTLs literature database was implemented starting from the identification of the articles published in international, peer-reviewed journals. The literature search was performed using Clarivate analytics' Web of Science-Core Collection™ (WoSCC) online platform, which is made up of more than 21,000 peer-reviewed journals worldwide (Web of Science Group, 2021). In this respect, other sources of information are freely available online, such as the ISC Event Bibliography (http://www.isc.ac.uk/event_bibliography/index.php), which is a database containing publications about seismology, but also other types of topics related to specific earthquakes, including landslides (Di Giacomo et al., 2014). However, since we focused exclusively on EQTLs, we used as search parameters on WoSCC a combination of significant keywords (e.g., *landslide, slope failure, earthquake, seismic, triggered, induced*) and Boolean search criteria applied to the "title", "abstract", and "keywords" of the articles (Reichenbach et al., 2018). A total of 810 articles published from April 1984 to February 2021 were collected and organized in the database. Each publication was verified to check its relevance for the topic of EQTLs. In most cases, it was sufficient to read the title and the abstract to verify whether an article was relevant for our purpose, but to prepare the final version of the database it was necessary a double-check of the manuscripts to reduce potential mistakes.

2.1 Data categories

Based on our experience and after a preliminary reading of approximately 10% of the articles, we identified a set of information that we consider significant for the analysis. We selected 3 major data categories (i.e., article information, article topic and earthquake information) further divided into sub-categories (Table 1).

Category		Sub-category	Counts
ID #	A1	Article identification number	810
Article information	B1	Publication year	1984-2021
	B2	Author(s)	1 to 35 per article
	B3	Title	
	B4	Journal	160
Article topic	C1	Main topic	4
	C2	Sub-topic	11
Earthquake information	D1	Earthquake ID	136
	D2	Earthquake name	
	D3	Earthquake time	
	D4	Earthquake country	35
	D5	Earthquake event type (single|multiple|unknown)	96|21|19
	D6	Earthquake focal mechanism (normal|normal-strike-slip|reverse|reverse-strike-slip|strike-slip|strike-slip-normal|strike-slip-reverse|unknown)	16|4|41|11|25|9|11|19
	D7	Moment tensor solution	97
	D8	Reference for focal mechanism	23
	D9	Richter local magnitude	
	D10	Richter surface-wave magnitude	
	D11	Moment magnitude	
	D12	MCS magnitude	
	D13	Epicentre latitude	
	D14	Epicentre longitude	
	D15	Hypocentre depth	
	D16	Earthquake catalogue (ANSS|NCEI/WDS|no data)	118|15|3

Table 1: Summary statistics of the categories and sub-categories used in the database. The column *Counts* provides the number of occurrences as given by the authors, when applicable.

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2.1.1 Article information

In the database, the information defined for each article are the following: publication year (B1); author(s) (B2); article title (B3) and journal name (B4). The first article of our search was published in April 1984 by Keefer and only 20 articles were published on the topic until 1999 (Figure 1). An increasing trend of the number of published articles can be noted in the following years, particularly from the late 2000s, with a peak in 2019 and 2020 (99 and 100 articles, respectively).

The 810 identified papers were published in 160 different peer-reviewed journals. The *Geological Society of America Bulletin* has published the least number of articles but for the longest period, considering that the first and last article were published in 1984 and 2020, respectively (Figure 2). *Engineering Geology*, *Landslides* and *Geomorphology* have published the largest number of articles (i.e., 233, which represents 28.8% of the total), covering a period from mid 1990s-early 2000s until February 2021. *Natural Hazards*, *Journal of Mountain Science* and *Bulletin of the Engineering Geology and the Environment* have published 105 papers (13.0% of the total), while *Natural Hazards and Earth System Sciences*, *Bulletin of the Seismological Society of America*, *Environmental Earth Sciences*, *Soil Dynamics and Earthquake Engineering* and *Geosciences* have published 118 papers (14.6% of the total). It is worth noting that *Geosciences* has published the largest annual number of papers with 14 articles in a little more than three years (2018-February 2021).
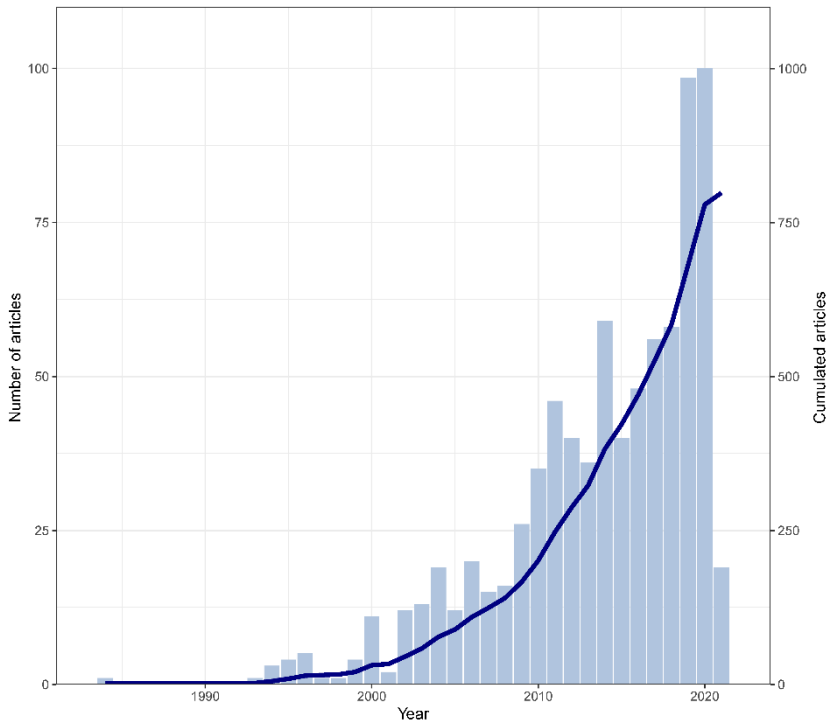
Figure 1: Analysis of the literature database listing 810 articles in the 37-year period from April 1984 to February 2021. Source of the articles search was the "Web of Science™" (formerly a Thomson Reuters™ product, now part of Clarivate™ Analytics). The graph shows the number of articles per year (vertical blue bars, left y-axis) and their cumulated number (solid blue line, right y-axis).
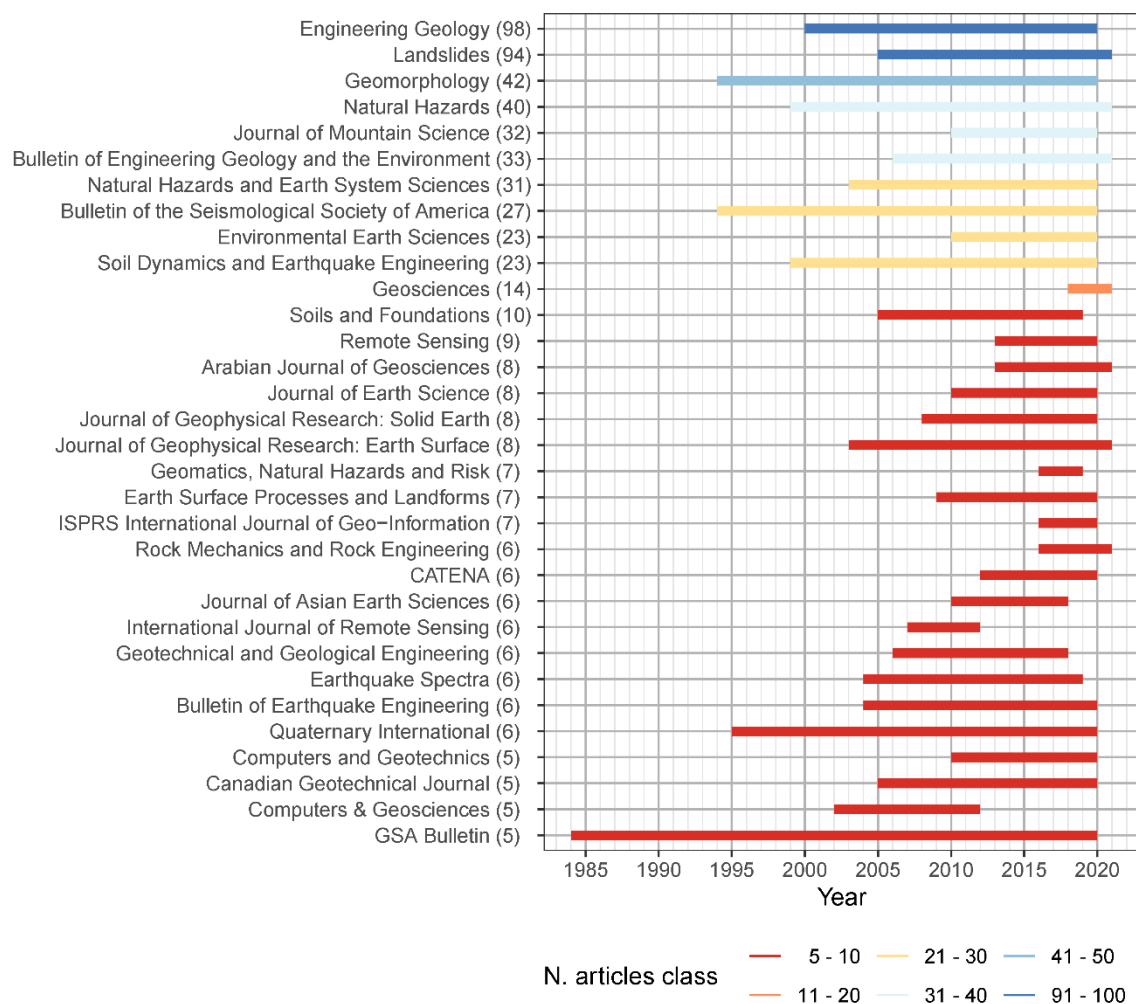
Figure 2: Ranking of top journals in terms of number of articles published on EQTLs, according to the literature database. The number of published articles is reported in brackets next to the journal name. The colour of horizontal bars indicates the number of articles in six classes.

Overall, 56.4% of the articles in the literature database were published in the above-mentioned eleven journals, whose scopes include the analysis of natural hazards, geological/geotechnical engineering, and geomorphology. Among these journals, only two (*Bulletin of the Seismological Society of America* and *Soil Dynamics and Earthquake Engineering*) specifically deal with seismology and earthquake engineering.

The analysis of the database revealed that the average number of authors for each paper varied over the years. Excluding the first article by Keefer (1984), the papers published until 2000 were written, on average, by 2-3 authors. In more recent years, the number increased to 4-5 authors, which suggests the need for different expertise to perform the wide range of research activities related to EQTLs.

2.1.2 Article topic

The articles collected in the database were classified in four categories considering the following main topics:

100 - *Regional landslide analysis*: articles focusing on the analysis of EQTLs over large areas.

- *Single landslide analysis*: articles focusing on the analysis of single mass movements.

- *Other*: articles presenting various types of research activities related to EQTLs, such as data presentation (e.g., Fortunato et al., 2012; Tanyas et al., 2017; Villani et al., 2018; Rodríguez-Peces et al., 2020), synthesis of historical information and review articles (e.g., Keefer, 1984; 2002; Bird and Bommer, 2004; Wasowski et al., 2011; Fan et al., 2019).

105 - *Not applicable*: articles on topics only partially related to EQTLs (see Sect. 3.1.3).

The articles included in the "regional" and "single landslide analysis" categories were further subdivided in sub-topics that characterize different aspects of the main research activity described in the manuscript (such as mapping, characterization, modelling etc.). In many cases more than one sub-topic has been attributed to a single article. For the "regional landslide analysis" the sub-topics can be summarized as follows:

110 1) *Regional mapping*: recognition of the spatial distribution of EQTLs.

2) *Regional landslide descriptive statistics*: statistical analysis of the main physical and geometrical features of EQTLs (e.g., number, extension, volume, run-out, type of movement, involved material).

3) *Regional susceptibility/hazard assessment*: modelling and zonation of susceptibility/hazard scenarios for EQTLs.

4) *Regional risk modelling*: assessment of the effects on human activities of EQTLs occurring over large areas.

115 5) *Regional landslide comparison*: analysis focused on the comparison between different landslide inventory maps, with the aim of evaluating general rules about earthquake induced landslide occurrence.

For the "single landslide analysis", the sub-topics are:

1) *Single failure mapping*: reconstruction of the surficial geometry.

2) *Single failure geotechnical characterization*: definition and description of the geotechnical parameters.

120 3) *Single failure geophysical characterization*: definition and description of specific parameters, which can be assessed using geophysical investigations (e.g., stiffness, shear modulus, moisture conditions etc.).

4) *Single failure modelling*: reconstruction of single landslide events triggered by earthquakes.

5) *Single failure impact/risk modelling*: analysis focused on the assessment of the effects induced by a single EQTL on human activities (e.g., damaging of buildings).

125 6) *Single landslide comparison*: analysis focused on the comparison between single landslides triggered by earthquakes.

2.1.3 Earthquake information

130   The 810 identified papers describe ground effects related to 136 earthquakes. For each earthquake we collected a set of data using as main source of information the ANSS Comprehensive Earthquake Catalog (ComCat), implemented by USGS (http://earthquake.usgs.gov/earthquakes/search/). In the catalogue, the available information depends on the date of occurrence. For earthquakes occurred before 1900 (18 events), it was possible to attribute only a broad localization of the epicentre, an estimation of the date of occurrence and the macroseismic intensity, which allows to quantify the shaking level

135   from observations of the effects on buildings, environment, and people (Masi et al., 2020). For earthquakes that occurred after 1900, it was instead possible to get more detailed information and it was possible to associate to each seismic event the data listed in Table 1: earthquake ID (D1), the name (D2), the time of occurrence (D3) in the format *yy-mm-dd-hh:mm-ss UTC* (Coordinated Universal Time), and the country of occurrence (D4). A distinction was made between single and multiple events (D5): an earthquake was considered as multiple when the seismicity nearby the main shock was characterized by at least 10

140   events with M_w (moment magnitude) ≥ 5. In the database we have also indicated the focal mechanism (D6). Specifically, the main deformation style of the earthquake-generating fault was defined using the Kaverina-type DC classification diagram (Kaverina et al., 1996), which considers 7 different fault mechanisms: normal, normal-strike-slip, reverse, reverse-strike-slip, strike-slip, strike-slip-normal, and strike-slip-reverse. From the Global Centroid Moment Tensor Catalogue (GCMTC) (https://www.globalcmt.org/), we retrieved the moment tensor solution (D7) for 97 out of 136 investigated earthquakes. We

145   used the moment tensor solution as input for the FMC software (Álvarez-Gómez, 2019), which allows to automatically generate a Kaverina-type DC classification diagram. In the cases where the moment tensor solution was missing, we defined the focal mechanism from the specific literature, if available (D8). The different types of magnitude, i.e., M_L-Richter local magnitude (D9), M_s-Richter surface wave magnitude (D10), M_w-moment magnitude (D11), and MCS-Mercalli–Cancani– Sieberg intensity scale (D12), were also added into the database, together with the epicentre coordinates (latitude - D13 and

150   longitude - D14) and the hypocentre depth (D15). For each record, we specified the source of information (D16). As mentioned above, most of the information derives from the ANSS catalogue but for several historical earthquakes, we used the National Centers for Environmental Information/World Data Service (NCEI/WDS) Global significant Earthquake Database (https://www.ngdc.noaa.gov/hazel/view/hazards/earthquake/search), which includes over 5,700 earthquakes from 2150 BC to the present.

155   ### 2.2 Structure and features of the web-GIS database

A dedicated web-GIS (http://194.119.218.119/it/map/a-web-gis-database-of-the-scientific-articles-on-e/qdjango/54/) was implemented to manage and consult the articles where geographical data (i.e., country and/or earthquake information) are available.

The web-GIS was implemented using G3W-SUITE (https://g3wsuite.it/en/g3w-suite-publish-qgis-projects/), a modular client-

160   server application that fully integrates the QGIS Python API and allows to publish and manage QGIS cartographic projects.

The web-GIS contains two geographic layers and two tables. The first geographical layer refers to the earthquakes, which are located according to their epicentre (latitude- D13 and longitude-D14); the second to the countries based on the "world_boundaries" shapefile (https://public.opendatasoft.com/explore/dataset/world-administrative-boundaries/export). The two tables ("articles_earthquake" and "articles_country") are associated to the corresponding geographic layers through a one-to-many relationship.

The web-GIS has a user-friendly interface consisting of different panels. In the left panel is possible to explore/use the following information/tools:

1) Metadata: general information on the web-GIS;
2) Charts: two different graphs showing the number of articles per country and number of articles per earthquake;
3) Search: a search tool which allows to perform alphanumeric searches on the available layers (i.e., "earthquake" and "world_boundaries");
4) WMS: where the user can customize the view using WMS services;
5) Map: which contains a list of the available layers (i.e., "articles_earthquake", "earthquake", "articles_country", "world_boundaries") and the corresponding legends. By right clicking on the name of each layer, it is possible to visualize the attribute table.

In the right panel there are commands for zooming in/out, measuring distances and areas, uploading new layers, and a snapshot tool. In this panel, the user can also perform queries (selecting the "i" icon) on specific earthquakes or countries, and visualize the main associated information.

3 Preliminary analysis of the literature database

In the following sub-chapters, we present and discuss a preliminary analysis on the main topics and sub-topics (Sect. 3.1) and on the earthquakes addressed and described in the articles (Sect. 3.2). In addition, in Section 3.3 we have evaluated the information on the addressed topics and the listed earthquakes for inferring general and specific aspects of the EQTLs scientific literature.

3.1 Analysis of article topic

The preliminary analysis of the articles included in the database allowed to recognize different themes and commonalities, and to group them according to main topics and sub-topics (see Sect. 2.1.2). In many cases, we assigned more than one main topic and/or sub-topic to a single article in relation to the variety of the performed analyses/activities.

As regards the main topics, Figure 3A reveals that the most represented category is "Regional landslide analysis", with more than half (53.8%) of the articles, followed by "Single landslide analysis" (27.2%), "Not applicable" (19.5%) and "Other" (3.4%).
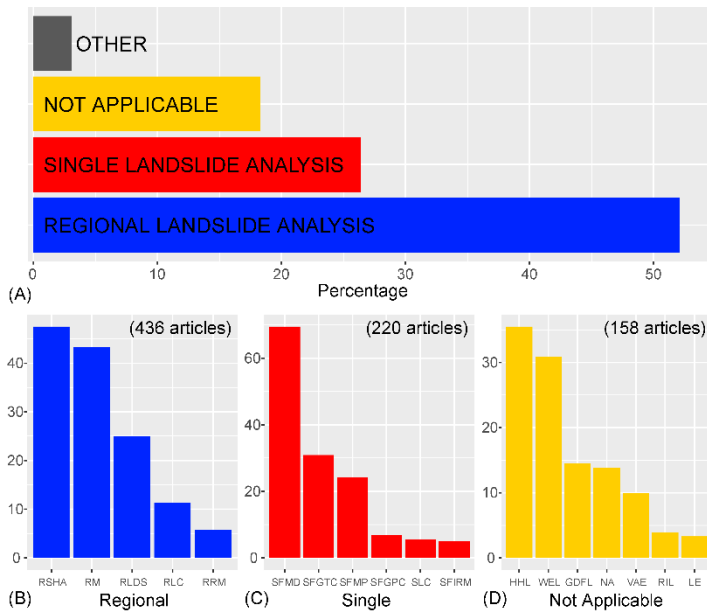
Figure 3: Percentage of articles with respect to the main topics (A) and sub-topics for "Regional landslide analysis" (B), "Single landslide analysis" (C) and "Not applicable" (D) categories. The percentage is calculated with respect to the total number of articles included in the considered category (in brackets). Legend: RSHA: regional susceptibility/hazard assessment, RM: regional mapping, RLDS: regional landslide descriptive statistics, RLC: regional landslide comparison, RRM: regional risk modelling, SFMD: single failure modelling, SFGTC: single failure geotechnical characterization, SFMP: single failure mapping, SFGPC: single failure geophysical characterization, SLC: single landslide comparison, SFIRM: single failure impact/risk modelling, HHL: historical/Holocene landslides, WEL: water environment landslides, GDFL: ground deformation, failure and liquefaction processes, NA: not applicable, VAE: vegetation and EQTLs, RIL: rainfall-induced landslides, LE: landscape evolution.

3.1.1 "Regional landslide analysis" category

The two most numerous sub-categories in the "Regional landslide analysis" category (Figure 3B) include articles which discuss "Regional Susceptibility/Hazard Assessment" analyses (RSHA) and "Regional Mapping" activities (RM) (47.0% and 43.8%, respectively). The third sub-category (Regional Landslide Descriptive Statistics - RLDS) presents statistical descriptions of EQTLs data and contains about a quarter of the articles (25.2%). Two further sub-categories discuss "Regional Landslide Comparison" (RLC) and "Regional Risk Modelling" (RRM) and contain only few articles (11.9% and 5.7%, respectively).

In the sub-category RSHA (205 articles), a large part of the articles uses and describes a modified versions of the Newmark (1965) model (e.g., Jin et al., 2019) or statistical methods such as logistic regression (e.g., Polykretis et al., 2019), artificial neural network (e.g., Tian et al., 2019), fuzzy logic (e.g., Razifard et al., 2019). In the set of articles that introduce modified versions of the Newmark model, the EQTL scenario related to a specific seismic event usually implies the exceedance of pre-established co-seismic displacement thresholds (Romeo, 2000), while in the group of statistical models, the outcome generally consists in susceptibility maps resulting from the weighting of different environmental factors (e.g., slope angle, geology,

vegetation cover, ground shaking intensity). In both cases the analysis of the EQTL phenomenon concerns almost exclusively

215 the triggering stage, while propagation and deposition processes are seldom examined (e.g., Guo et al., 2014). In addition, no specific methodological variations are presented with respect to the investigated landslide type (e.g., rockfall, earthflows etc.). The high number of papers included in the RM sub-category (191 articles) highlights the importance of landslide inventories for analyses over large areas. In this respect, it is important to point out the presence of different online catalogues which report information on EQTLs for recent and historical earthquakes. At global scale, it is worth mentioning the "Open Repository of

220 Earthquake-triggered Ground Failure Inventories" (Tanyas et al., 2017), which reports EQTLs and liquefaction effects data for 363 earthquakes, or the "Earthquake Environmental Effects Catalogue" (Guerrieri et al., 2015), which collects information about environmental effects triggered by specific seismic events, whose intensity is expressed according to the ESI (Environmental Seismic Intensity) scale (Michetti et al., 2007).

81 out of the 191 RM articles can be also classified within the third sub-category RLDS, since they include not only a

225 description of one or more EQTL inventories, but also a statistical analysis of the features of the mapped landslides (e.g., Roback et al., 2018). Conversely, other 66 RM articles are exclusively focused on mapping procedure, which are performed with different methods and techniques such as: field investigation (e.g., Martino et al., 2017), analysis of aerial imagery (e.g., Saito et al., 2018) and satellite data (e.g., Hu et al., 2019).

As regards the RLC and RRM sub-categories, the relatively low number of articles (52 and 25, respectively) suggests the high

230 specificity of the themes. In the first case, the comparison between landslide inventories can be performed for evaluating potential differences among earthquakes occurring in the same area (e.g., Jibson et al., 2020) or for inferring general rules (Tanyas and Lombardo, 2020) and/or correlations, e.g., magnitude vs. affected area (e.g., Marc et al., 2017), ground motion vs. landslide size (e.g., Jibson and Tanyas, 2020). In the case of RRM articles, the analyses are focused on specific anthropic elements such as buildings, roads, and railways (e.g., Vega and Hidalgo, 2016) or can be framed within a wider risk assessment

235 (e.g., Martino et al., 2020).

3.1.2 "Single landslide analysis" category

The largest number of articles (153 out of 220) within the "Single landslide analysis" category (Figure 3C) is included in the "Single Failure Modelling" (SFMD) group. These articles thoroughly investigate the triggering (e.g., Zhang et al., 2018) and/or

240 the propagation process (e.g., Li et al., 2017) of single landslide events induced by specific seismic inputs. Although different types of approaches have been proposed by the authors, e.g., laboratory experimental testing (e.g., Pu et al., 2020), numerical modelling still represents the most widely used technique. Over the years, numerous types of increasingly sophisticated models have been developed (Jibson, 2011), which allowed to simulate complex physical processes related to EQTLs, as for example progressive slope failure induced by strain-softening behaviour (e.g., Islam et al., 2019), dynamic fragmentation (e.g., Zhao

245 and Crosta, 2018), and pore-water pressure variation on the sliding surface (Huang et al., 2019).

The SFMD sub-category also comprises 39 out of 68 articles included in the second sub-category ("Single Failure Geotechnical Characterization"-SFGTC). In fact, numerical modelling often requires a detailed definition of the geotechnical parameters of

the landslides body, which can be measured directly on field (e.g., Gratchev and Towhata, 2010) or estimated through laboratory tests and parametric analyses (e.g., Dang et al., 2016). It is important to specify that, in many cases, the authors defined the input parameters of the numerical model simply based on literature values referred to the same or similar landslide event (e.g., Nian et al., 2020).

Similarly, as described for regional scale, "Single Failure MaPping" (SFMP) sub-category includes all those articles dealing with mapping of a single landslide body (e.g., Bozzano et al., 2008). Within this sub-category it is also possible to find almost all the articles belonging to the "Single Failure GeoPhysical Characterization" (SFGPC). This point suggests how geophysical investigations are often associated with the detailed reconstruction of the geometry of the landslide (e.g., Havenith et al., 2002). As regards "Single Landslide Comparison" (SLC) and "Single Failure Impact/Risk Modelling" (SFIRM), we identified a relatively low number of articles (12 and 11, respectively), as in the case of regional scale analyses. In the first instance, the comparison concerns landslides occurred during the same earthquake (e.g., Nakamura et al., 2014) or in response to other events occurred in different regions (e.g., Aydan, 2016). In SFIRM articles, the effects of an EQTL on human activities can be estimated after a specific event (*ex post* assessment e.g., Cui et al., 2012) or *a priori* through the reconstruction of specific single landslide risk scenarios (e.g., Mousavi et al., 2011).

3.1.3 "Not applicable" category

As mentioned above, the category "Not applicable" contains articles which address and discuss themes only partially related to EQTLs. Considering the not negligible number of articles (158), we performed their analysis and evaluation. On the contrary, we decided to disregard the "Other" category, since the low number of articles (28) did not allow us to infer general aspects and significant commonalities.

The examination of the article classified as "Not applicable" consented to identify different sub-categories (Figure 3D). The most numerous ("Historical Holocene Landslides"-HHL) contains 53 articles (33.5%) dealing with landslides occurred in historical times (i.e., before 1900) and, more generally, during the Holocene. In case of historical failures, only generic information about the triggering earthquake is available, while in the second one (landslide occurred during the Holocene), it is often difficult to recognize with certainty the earthquake as triggering factor. In these articles, the authors often use terms that refer to the possible nature of the landslide trigger, such as: "was probably triggered" (Pérez-López et al., 2019) or "most likely triggered" (Lv et al., 2014). In this group, several authors also describe dating techniques, such as dendrochronological (e.g., Struble et al., 2020), lichenometric (e.g., Pérez-López et al., 2019) and isotopic analyses (e.g., Kojima et al., 2014). For landslide events occurred in historical times, archival records often represent the main source of information (Koukouvelas et al, 2020). The back-analysis of such events was also used to assess the intensity and the location of historical earthquakes as described, for instance, by Rodríguez-Peces et al., 2011 for the 1755 Lisbon (Portugal) and 1884 Arenas del Rey (Spain) earthquakes.

Beyond the historical landslides, we also decided to include in the "Not applicable" category all those articles dealing with landslides related to the geological hazard chain potentially resulting after an earthquake (Fan et al., 2019). In this respect, we identified three sub-categories:

1) Water Environment Landslides" (WEL): this sub-category comprises 47 articles (29.7%) specifically focused on the secondary effects of EQTLs in water environments, such as landslide-induced tsunamis (e.g., Takagi et al., 2019) and floods related to river landslide dams (e.g., Fan et al., 2012). In case of historical earthquakes, EQTLs in water environments are generally used as evidence for confirming past tsunamis (e.g., Kitamura et al., 2020) and river damming events (e.g., Ehteshami-Moinabadi and Nasiri, 2019) or, more generally, the occurrence of one or multiple earthquakes in a specific area (e.g., Goto et al., 2010).

2) Rainfall-Induced Landslides (RIL): the 9 articles (5.7%) included in this sub-category were classified as "Not applicable" since earthquake represents a predisposing factor for subsequent rainfall-induced failures, i.e., post-seismic landslides (Tanyas et al., 2021). In general, these papers deal with comprehensive landslide hazard assessments (e.g., Hong and Adler, 2007) or cascading effects' evaluations (e.g., Tunas et al., 2020).

3) Landscape Evolution (LE): these 8 articles (5.1%) investigate the role of EQTLs as a surface process in the framework of landscape evolution, also considering other morphogenetic processes as, for example, tectonic uplift (e.g., Gallousi et al., 2007; Li et al., 2019) or fluvial sediment discharge (e.g., Hovius et al., 1997; Marc et al., 2016).

Another sub-category of articles classified as "Not applicable" includes works mainly focused on other earthquake-induced ground effects which can occur concurrently with EQTLs. In particular, 22 articles (13.9% of the total) describe and discuss EQTLs together with co-seismic Ground Deformations and Failure/Liquefaction processes (GDFL) (e.g., He et al., 2020). However, it is important to stress that liquefaction is a relevant and important earthquake-induced ground effect which frequently occurs in flat areas, thus independently of EQTLs. Many scientific articles are specifically focused on this topic, but they are not listed in our database since the word "liquefaction" is not one of the searching keywords.

The analysis of "Vegetation And EQTLs" (VAE) is addressed by 15 articles (9.5%) and represents another sub-topic. These articles are focused on the stabilising effect of vegetation recovery at landslide sites after earthquake events (Yang et al., 2018) or, conversely, on vegetation change/alteration induced by EQTLs (e.g., Cheng et al., 2012).

Finally, 21 articles were classified as fully "Not Applicable" (NA) since the addressed topic is not related to EQTLs, such as the dynamic response of slopes based on in-situ monitoring systems (Moore et al., 2011; Lenti et al., 2015) or the evaluation of the hydrological response of landslide bodies under seismic loading (Beyabanaki et al., 2016; O'Brien et al., 2016).

3.2 Analysis of earthquake information

As mentioned in Sect. 2.1.3, the 810 articles collected in the database discuss and present ground effects of 136 earthquakes, mainly located in Italy, Japan, USA, and China (Figure 4). The earthquakes analysed in the articles agrees with the typical distribution of the main seismicity at the global scale (Figure 5), with most of the events located along the boundaries of the

tectonic plates. About 80% of the world's seismicity is situated along the circum-Pacific margin, in correspondence of subduction zones, where earthquakes are caused by thrust-type and transcurrent-type faults (Toriumi, 2021). The focal

315 mechanisms of the 136 earthquakes are predominantly associated to reverse/reverse-strike-slip faults (52 events, which correspond to 38.2% of the total) and, secondly, to faults with a prevalent strike-slip component (45 events, which correspond to 33.1% of the total) (Table 1 and Figure 6). Moreover, the reverse-faulting mechanism characterizes not only most of the identified events, but also the strongest ($M_w \geq 8$) ones, in agreement with the general observation for which the largest earthquakes mainly occur in subduction zones (Funiciello et al., 2020).

320 As regards the intensity, 46 earthquakes (33.8% of the total) have a $M_w \geq 7$ (Table 2). Although it may seem like a large number, the data collected between 2000 and 2021 (https://www.usgs.gov/programs/earthquake-hazards/lists-maps-and-statistics) indicate that the average yearly number of $M_w \geq 7$ earthquakes in the world is 15. This implies that strong earthquakes occurring worldwide are more numerous than those effectively analysed by the scientific community, at least in the framework of EQTLs. This can be explained considering that, in principle, the investigated earthquakes are those more impactful for

325 human activities. In the specific case of EQTLs, the scientific interest generally focuses on earthquakes occurring in populated areas or nearby. In this respect, most of the articles included in the database deal with earthquakes occurred in the Asian inland and surrounding areas (Figure 5). The devastating 2008 Wenchuan earthquake (M_w 7.9) is certainly the most studied event (180 articles), while the 1999 Chi-Chi earthquake (M_w 7.7) is the second one, although with a much lower number of articles (59) (Table 3). The most studied earthquake which did not occur on the Asian continent is the 1994 Northridge earthquake

330 (M_w 6.7) with 13 articles. In general, earthquakes occurred in China are the most studied events in the framework of EQTLs (i.e., 256 articles distributed among 13 earthquakes), followed by those located in Japan (i.e., 78 articles for 16 earthquakes) (Figure 7A-B). It is interesting to note that the earthquakes occurred in Italy, albeit more numerous (i.e., 19 events), are not as studied, since only 40 articles address these events, with a maximum value of 10 articles for the 2016 Amatrice earthquake (M_w 6.2) (Figure 7C). This point can be explained considering that earthquakes tend to arouse scientific interest mainly at

335 national level. In this sense, only 2 out of 40 articles do not include Italian authors. As regards the 16 earthquakes occurred in the United States (Figure 7D), only the 1994 Northridge earthquake has been examined in more than 5 articles (Table 3). Thus, if we consider that only 30 articles of the database focus on earthquakes in USA, we can assert that these events, despite the high magnitude (average M_w 7.1), have been analysed to a lesser extent, at least in relation to EQTLs.

Finally, it is interesting to highlight that 18 out of 136 earthquakes have been labelled as historical (i.e., before 1900). Only 20

340 articles focus on these events, with a maximum value of 4 papers for the 1786 Moxi earthquake (Table 4). Based on what explained in Sect. 3.1.3, these articles have been classified as "Not applicable" since they concern historical landslides. Specifically, 6 articles can be also included in the sub-category "water environment landslides", while only one article, which describes the effects of the 1811-1812 New Madrid earthquakes (Tuttle and Barstow, 1996), can be linked to the "ground failure-deformation/liquefaction" sub-category.

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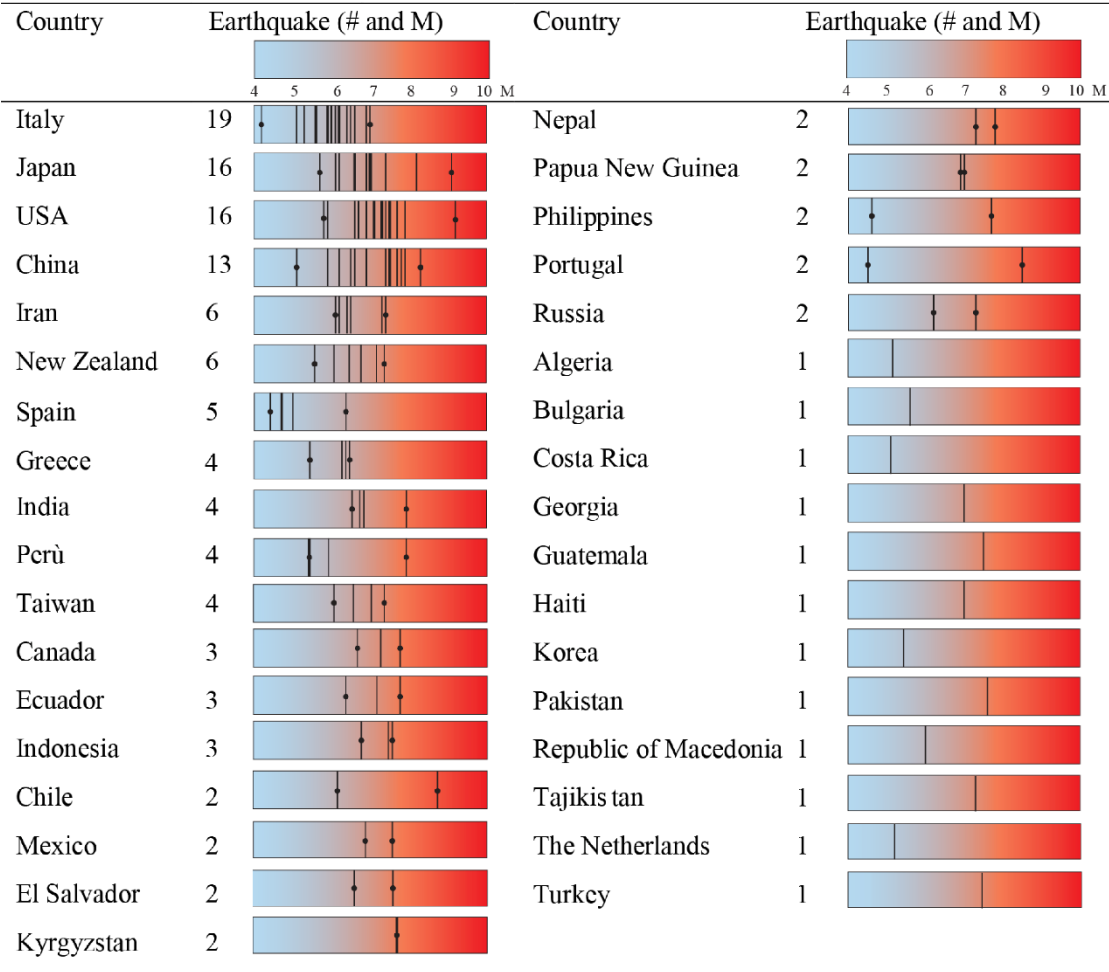
Figure 4: Number of earthquakes listed in the database for each country. The magnitude of each event is reported in the coloured bar. For each country, the lines with the black dot show the first and the last earthquake.

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Moment magnitude	Counts
$4 \leq M_w < 5$	2
$5 \leq M_w < 6$	18
$6 \leq M_w < 7$	48
$7 \leq M_w < 8$	36
$8 \leq M_w < 9$	8
$M_w \geq 9$	2

Table 2: Number of earthquakes identified for different intervals of moment magnitude (M_w).
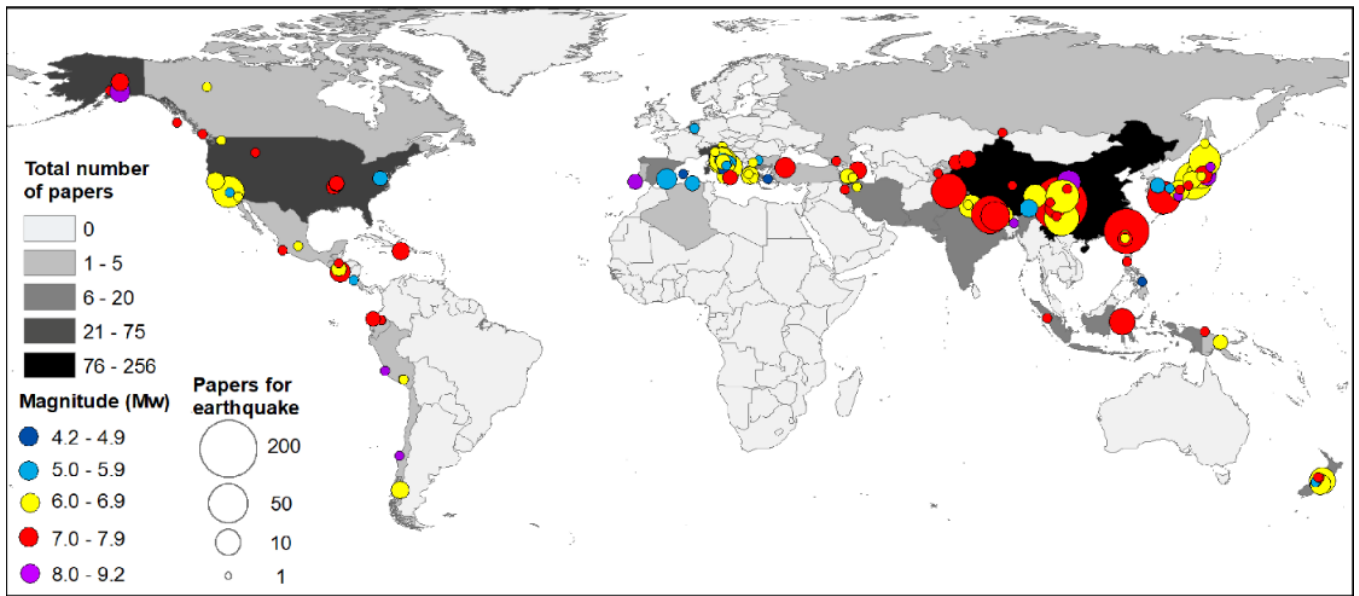
Figure 5: Spatial distribution of the 136 earthquakes identified in the literature search. Colour indicates the magnitude, while the size of the circle is proportional to the number of articles dealing with each seismic event. Countries are classified based on the number of articles collected in the database.
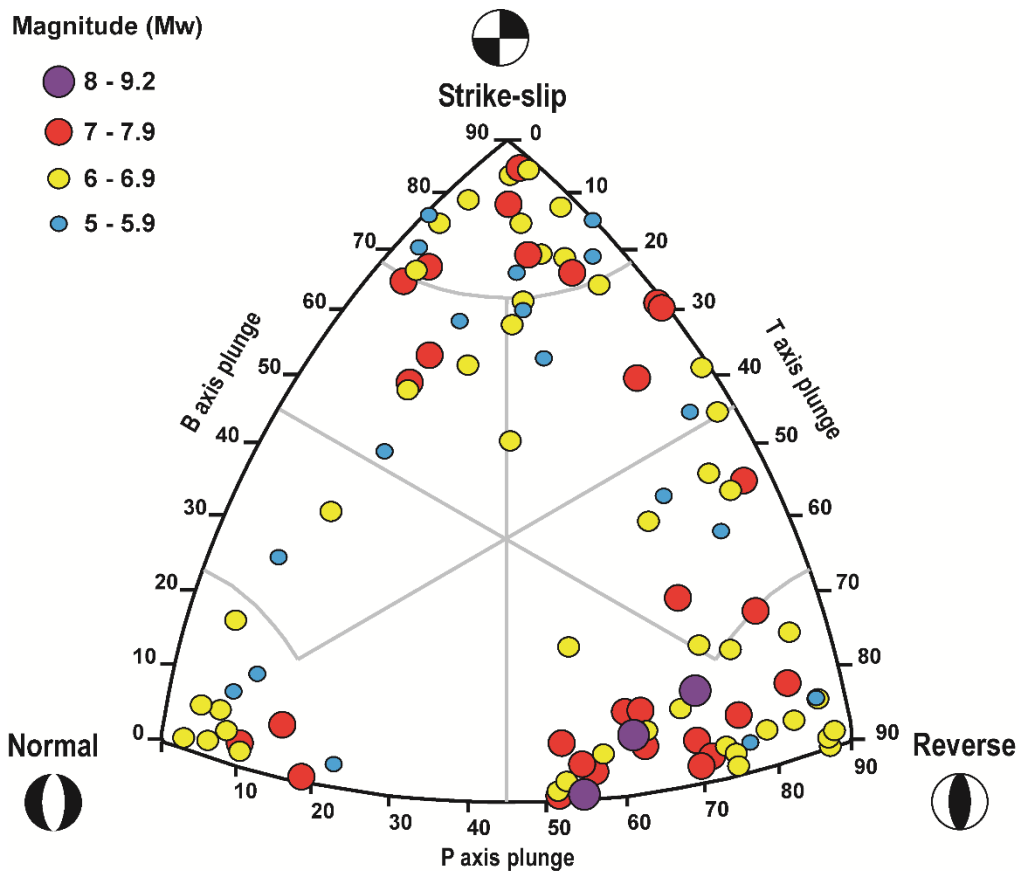
Figure 6: Definition of the focal mechanism of 97 out of 136 investigated earthquakes according to the Kaverina-type DC classification diagram. Several earthquakes are not plotted due to the lack of information concerning P, T and B centroid moment tensor axes.

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ID	Earthquake	Country	Earthquake date	M_w	N. articles
chin_1	Wenchuan	China	2008-05-12 06:28:01 UTC	7.9	180
taiw_1	Chi-Chi	Taiwan	1999-09-20 17:47:18 UTC	7.7	59
nep_1	Gorkha	Nepal	2015-04-25 06:11:25 UTC	7.8	28
jap_1	Niigata-Chuetsu	Japan	2004-10-23 08:56:00 UTC	6.6	27
chin_2	Lushan	China	2013-04-20 00:02:47 UTC	6.6	24
pak_1	Kashmir	Pakistan	2005-10-08 03:50:40 UTC	7.6	19
chin_5	Wenping	China	2014-08-03 08:30:13 UTC	6.2	18
chin_8	Jiuzhaigou County	China	2017-08-08 13:19:49 UTC	6.5	17
jap_2	Kumamoto	Japan	2016-04-15 16:25:06 UTC	7	16
jap_6	Hokkaido Eastern Iburi	Japan	2018-09-05 18:07:59 UTC	6.6	13
usa_4	Northridge	USA	1994-01-17 12:30:55 UTC	6.7	13
nep_2	Gorkha_2	Nepal	2015-05-12 07:05:19 UTC	7.3	11
ita_4	Amatrice	Italy	2016-08-24 01:36:32 UTC	6.2	10
jap_4	Iwate–Miyagi Nairiku	Japan	2008-06-13 23:43:45 UTC	6.9	10
indo_1	Palu	Indonesia	2018-09-28 10:02:45 UTC	7.5	8
ita_6	Norcia	Italy	2016-10-30 06:40:18 UTC	6.6	8
chin_3	Minxian-Zhangxian	China	2013-07-21 23:45:56 UTC	5.9	7
nze_1	Kaikōura	New Zealand	2016-11-14 00:34:22 UTC	6.5	7
ita_1	Irpinia	Italy	1980-11-23 18:34:53 UTC	6.9 (M_s)	6
chin_4	Haiyuan	China	1920-12-16 12:05:55 UTC	8.3	5
chin_6	Yushu	China	2010-04-13 23:49:38 UTC	6.9	5
ind_1	Chamoli	India	1999-03-28 19:05:11 UTC	6.6	5
ita_5	Castelsantangelo sul Nera	Italy	2016-10-26 19:18:08 UTC	6.1	5
ita_12	Umbria-Marche	Italy	1997-09-26 09:40:26 UTC	6	5

Table 3: List of the main characteristics of the earthquakes analysed in more than 5 articles.

375

Total number of papers

- 0
- 1 - 5
- 6 - 20
- 21 - 75
- 76 - 256

Magnitude (Mw)

- 4.2 - 4.9
- 5.0 - 5.9
- 6.0 - 6.9
- 7.0 - 7.9
- 8.0 - 9.2

Papers for earthquake

- 200
- 50
- 5
- 1
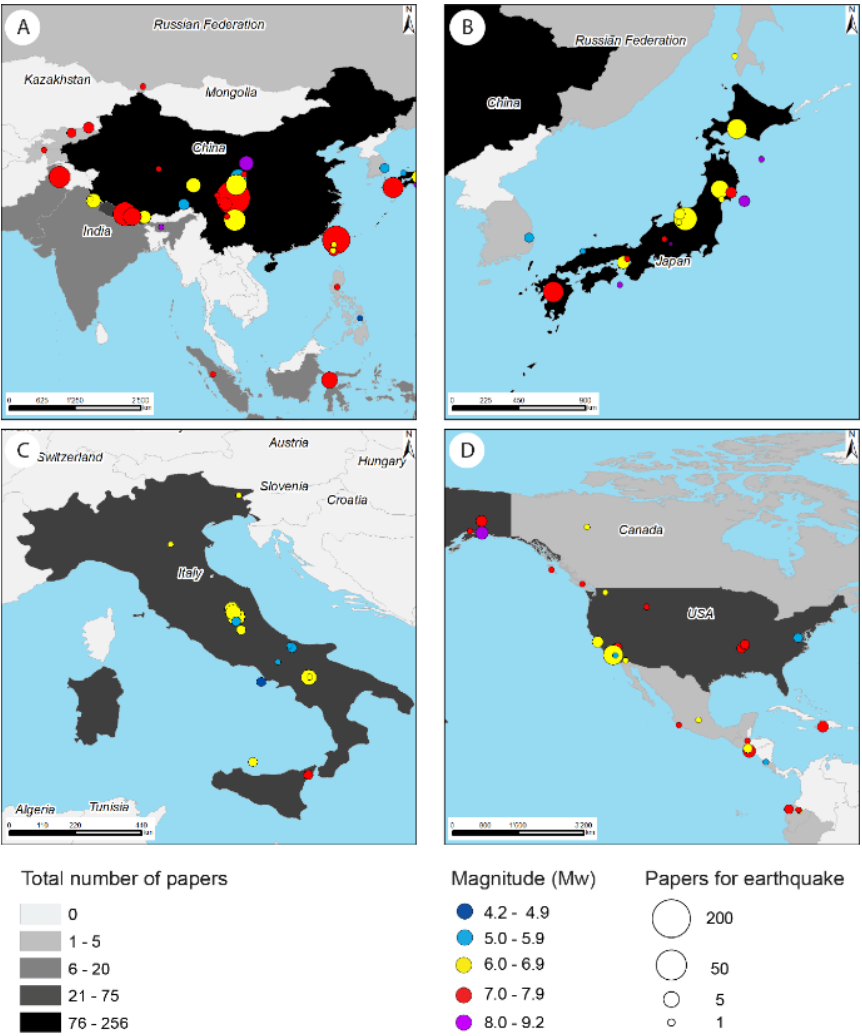
Figure 7: Spatial distribution of the earthquakes listed in the database for four countries, i.e., China (A), Japan (B), Italy (C), and USA (D). Colour indicates the magnitude, while the size of the circle is proportional to the number of articles dealing with the earthquake. Countries are classified based on the number of articles collected in the database.

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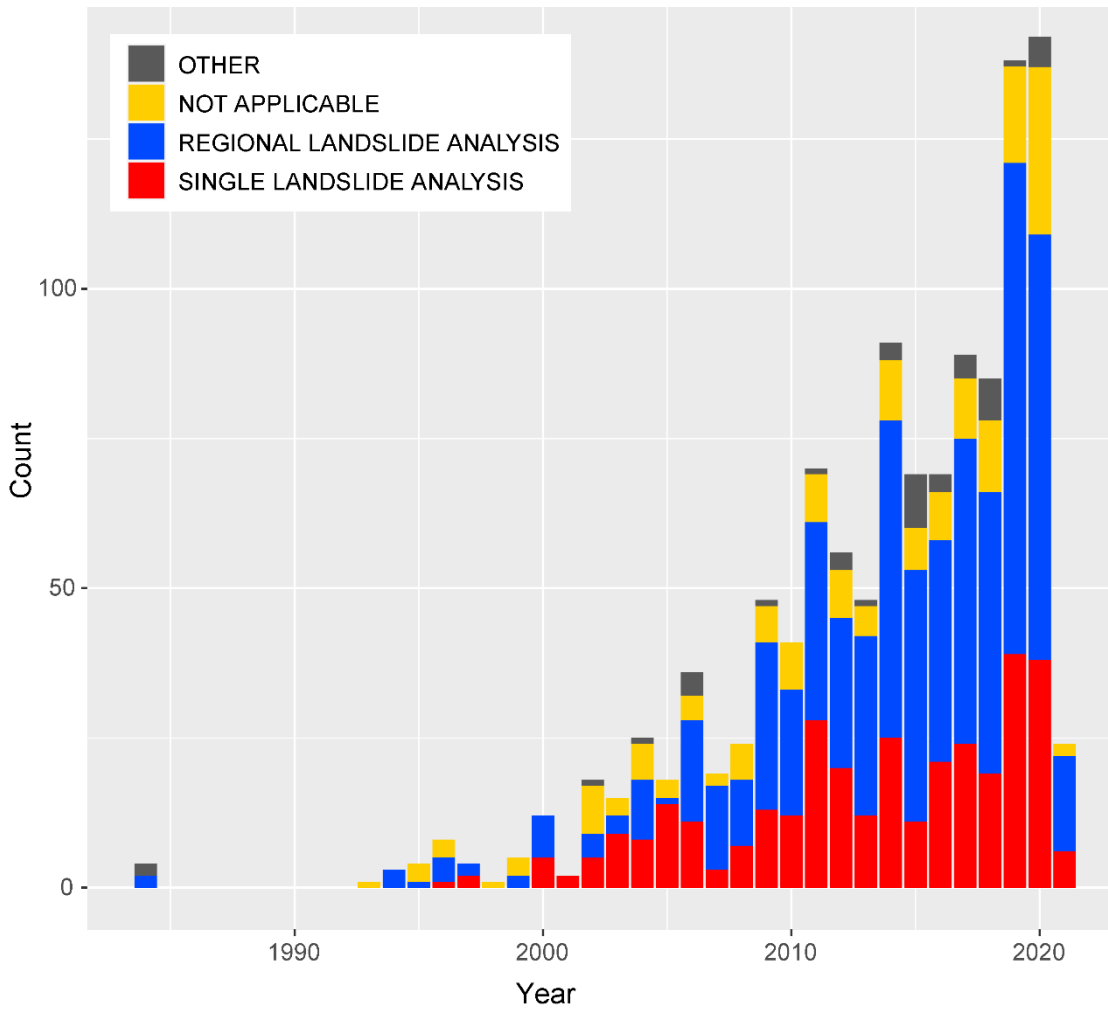
ID	Earthquake	Country	Earthquake date	M_s	N. articles
chin_7	Moxi	China	1786-06-01	7.75	4
ita_13	Calabria	Italy	1783-02-06	5.9	2
por_2	Lisboa	Portugal	1755-11-01	8.5 (M_w)	2
usa_9	New Madrid 1	USA	1811-12-16	8.5	2
usa_10	New Madrid 2	USA	1812-01-23	8.4	2
usa_11	New Madrid 3	USA	1812-02-07	8.8	2
chin_10	Xichang	China	1850-12-09	7.5	1
chin_11	Tongwei	China	1718-06-19	7.5	1
ind_3	Assam	India	1897-06-12	8.7	1
indo_3	Ambon	Indonesia	1674-02-17	6.8	1
ita_16	offshore Apulia	Italy	1743-02-20	6.9	1
ita_17	offshore Sicily	Italy	1693-01-09	6	1
jap_13	Keichou-Fushimi	Japan	1596	7	1
jap_15	Totomi-Jishin	Japan	714	unknown	1
jap_16	Hietsu	Japan	1858-04-09	7.45	1
jap_9	Hoei	Japan	1707-10-28	8.4	1
spa_2	Arenas del Rey	Spain	1884-12-25	6.5 (M_w)	1
usa_13	Lake Chelan	USA	1872-12-15	6.8 (M_w)	1

Table 4: List of historical earthquakes collected in the database.

3.3 Combined analysis of article topics and earthquake information

Based on the above information, we have performed combined analyses to evaluate: i) the addressed main topics and sub-topics over time and ii) to evaluate the type of scientific evaluation performed for specific earthquake events. Figure 8 reveals that from the second half of 2000s the "regional landslide analysis" articles have always been more numerous than "single landslide analysis" ones, with an almost constant proportion during the entire period. This confirms the increasing use, in the last decades, of remote sensing data, especially satellite imageries, for the generation of EQTLs inventories (Fan et al., 2019). This point, alongside with the development of calculation skills/performances of advanced computers, greatly enhanced and expedited the analysis of terrain data, especially over large areas.

400 **Figure 8: The graph shows the temporal distribution of the main topics addressed by the authors in the 37-year period from April 1984 to February 2021.**

As regards the analysis of specific earthquakes events, we selected the first five earthquakes listed in Table 3 (i.e., Chi-Chi 1999, Niigata-Chuetsu 2004, Wenchuan 2008, Lushan 2013 and Gorkha 2015), for which more than twenty articles were

405 published. The first three occurred more than ten years ago and can be considered suitable for evaluating potential topic trends over the years.

In terms of main topics, in the years immediately after the Chi-Chi earthquake, only "single landslide analysis" articles were published (Figure 9). On the contrary, in the first years after Niigata-Chuetsu and Wenchuan earthquakes, also "regional landslide analysis" studies were performed. For Wenchuan earthquake, the number of "regional landslide analysis" articles are

410 even greater than that of "single landslide" ones until 2014, i.e., six years after the event. The increasing trend of "regional landslide analysis" articles is furthermore confirmed by the Lushan 2013 and Gorkha 2015 events. This result suggests that, in

the recent years, researchers have performed regional analyses as a priority with respect to slope-scale studies. Such a preference may be put in relation with the increasing availability of remote sensing data and high-performance computational tools, which enhance the execution of regional-scale analyses in a short time. On the contrary, the collection of data generally employed for slope-scale analyses can be extremely time-consuming, thus affecting the timing of publication. Within "regional" articles we also noticed that, in general, "mapping" (RM) is the prevailing activity in the first period after the event, while "modelling" (RSHA) tends to increase over time. RM articles can still be published also several years after the event: these works can include updates of existing inventories (e.g., Chen et al., 2020) or *ex-novo* mapping for in-depth analyses of landslide activity (e.g., Liu et al., 2020).

As regards "single landslide analysis" articles, "modelling" (SFMD) is the prevailing activity and shows an increasing trend over the years (Figure 9). Alongside "modelling", "geotechnical characterization" (SFGTC) and "mapping" (SFM) are generally carried out, especially in the first years after the Chi-Chi and Niigata-Chuetsu earthquakes, while other types of sub-topics are substantially secondary. In the case of Wenchuan, different SFM articles have been published also in recent years (e.g., Cui et al., 2017). In this respect, although more than 60,000 landslides have been triggered during the event (Gorum et al., 2011), only few failures have been investigated individually. This leaves room for the verification to the real triggering and conditioning mechanisms, which as a matter of fact rely only on a few studies. Among these, the Daguangbao landslide is the most studied (e.g., Luo et al., 2020), probably due to its great size (7.5×10^8 m^3). As regards Lushan and Gorkha event, very few articles have been published in the framework of "single landslide analysis" topic; thus, it was not possible to observe any specific trend.

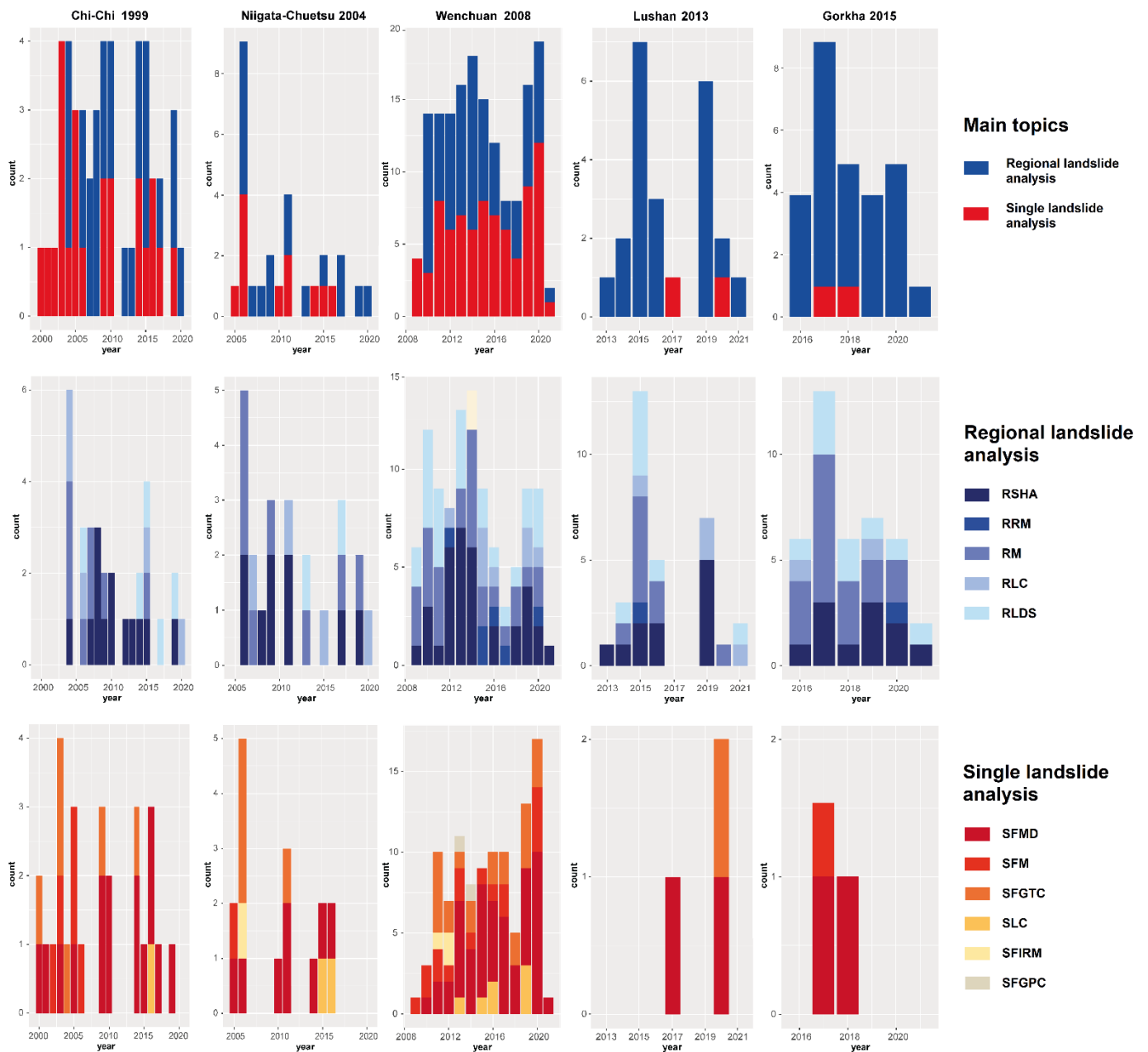



Figure 9: Temporal analysis of the main topics (first row), "regional" (second row) and "single landslide" sub-topics (third row) addressed by the articles dealing with Chi-Chi 1999 (first column), Niigata-Chuetsu 2004 (second column), Wenchuan 2008 (third column), Lushan 2013 (fourth column), and Gorkha 2015 earthquake (fifth column)

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4 Final remarks and conclusions

In this work, we present a comprehensive database of the main scientific articles published in the last four decades on the EQTLs theme. After the identification of 810 papers, the database was compiled in a GIS environment specifying, for each article, different types of information. Great effort was dedicated to the identification of the addressed earthquakes and to the articles' grouping with respect to main topics and sub-topics relevant to EQTLs. In this sense, we highlighted that more than 50% of the articles focus on regional analyses which, in turn, are equally distributed among "modelling" and "mapping" sub-topics. On the contrary, "single landslide analysis" works, which represent just over a quarter of the total number of articles, deal more with modelling-type activities and, secondarily, with geotechnical characterization of the landslide body. As regards the addressed earthquakes, although great part of the 136 identified events occurred in four different countries (Italy, Japan, United States and China), earthquakes which took place in China are by far the most studied events (256 articles), even if 180 out of these 256 articles analyse the 2008 Wenchuan earthquake. Finally, by analysing the addressed topics over time for the five main earthquakes (Chi-Chi 1999, Niigata-Chuetsu 2004, Wenchuan 2008, Lushan 2013 and Gorkha 2015), we pointed out an increasing trend of "regional landslide analysis" articles in the last years, alongside with a growing use of modelling approaches both for regional and single landslide-scale analyses. However, it is important to stress that the considerations presented in this work just represent general inferences resulting from the analysis of the collected articles. More specific observations would require an in-depth, critical analysis of the articles, which is beyond the scope of the present study. In fact, this work can be considered as a starting point for further analysis and investigations and is proposed to the expertise and a general reader interested in a broader view of EQTLs.

As regards future activities, it is important to notice that the database can be updated very promptly. In this respect, authors invite all the readers to report not only new-published articles on EQTLs theme, but also articles that were published in the past and were not included in the database due to shortcomings in the use of keywords during the literature search on Web of Science database. Future versions of the database can be also improved through the integration with other sources of information, such as the ISC Event Bibliography. In conclusion, the here-presented web-GIS database can represent a powerful tool for performing cross-correlated literature searches focused on specific main topics/sub-topics in relation to given earthquake events and/or study areas.

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Authors contribution

Luca Schilirò: conceptualization, data curation, writing-original draft **Mauro Rossi:** conceptualization, data curation, software, writing-review and editing **Federica Polpetta:** data curation, writing-review and editing **Federica Fiorucci:** web-GIS conceptualization and set-up, data curation, writing-review and editing **Carolina Fortunato:** data curation, writing-review and editing **Paola Reichenbach:** conceptualization, data curation, writing-review and editing, supervision, project administration

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