Natural Hazards (2023) 119:1091–1106
https://doi.org/10.1007/s11069-022-05627-x

ORIGINAL PAPER

Earthquake fatalities and potency

Max Wyss[1] · **Michel Speiser**[1] · **Stavros Tolis**[1]

Received: 1 May 2022 / Accepted: 15 September 2022 / Published online: 21 October 2022

Abstract
We have compiled a new catalogue of earthquake fatalities for the world, covering the period 856 BC to March 2022, listing 2795 reports. We estimate that the reporting of fatal earthquakes is complete for events with more than 16 fatalities since 1927. The total number of fatalities recorded is 8,336,526. 117 countries have reported at least one earthquake with one fatality or more. 77 and 52 countries have reported more than 100 and 1000 earthquake fatalities, respectively. Caution has to be exercised in estimating what earthquake disasters are in store for a given country because the 95 year period of high quality recording is about an order of magnitude shorter than return times of great earthquakes. Nevertheless, we introduce the earthquake potency for a country, defined as the sum of recorded fatalities divided by the number of earthquakes that it took to accumulate them, which equals the average earthquake disaster size in a given country, in units of fatalities per event. Potency is listed based on all known fatal earthquakes and also based on those since 1927. Both lists have their shortcomings, but provide estimates of what size of future earthquake disaster is likely in store for a particular country. For rescue purposes, it is important to realize that small earthquake, M 5 ± 0.5, can cause significant numbers of fatalities.

Keywords Earthquake fatalities · Earthquake risk reduction · Potency of fatal earthquakes

1 Introduction

Earthquakes have caused fatalities, mostly from collapsing buildings, from the time when cultures began to build structures substantial enough to kill inhabitants when shaken. In order to mitigate earthquake impacts, one needs to know where and how significant earthquakes have affected the population. To be well informed, one would like to know fatality records over periods longer than earthquake cycles on major faults. However, rupture cycles last hundreds and thousands of years, far longer than humanity's reliable record of earthquakes. In particular, early records of earthquake fatalities are scantily available, and then only from cultures with preserved documents and partial keeping of records (Utsu 2002).

✉ Max Wyss
max@maxwyss.ch

[1] International Centre for Earth Simulation (ICES Foundation), Geneva, Switzerland

For a review of current knowledge, we have compiled a new list of fatal earthquakes worldwide. The completeness of this list increases as a function of time, from very poor to almost complete, at present. Numerous earthquakes with only one fatality are reported currently. Nevertheless, earthquakes undoubtedly still kill people in remote areas, without the world at large knowing about it.

The accuracy of fatality counts in the largest, most important earthquake disasters is necessarily poor, even at present. Not all victims are found, or counted before they are buried. An example of the medical response in a recent Iranian earthquake, and the difficulties to keep accurate records is presented by (Farahbod and Wyss 2017). The order of magnitude of a disaster is all one can rely on. The number of victims in early historical counts is highly uncertain for some countries, but we have included reports on all fatal earthquakes that could be identified from all catalogues available to us because we know of no reason to exclude any of them.

2 The catalogue of deadly earthquakes

The catalogue we present here (Online Appendix A) is a combination of the list published by Utsu (2002) plus the unpublished extension up to 2004 by the same author, plus the list contained on the website of the National Oceanic and Atmospheric Administration (NOAA) (Noaa 2022), and lists for Greek (Papazachos et al. 2000; Papazachos and Papazachou 2003), identified as from GRC, and Italian fatal earthquakes (Guidoboni et al. 2018, 2019), identified as from INGV. For earthquakes that were reported by two sources, the entry that had more information was selected (for example when a value was given for hour of occurrence in one source only). In cases when the same number of parameters were given, we selected the entry by Utsu as default. We corrected the origin time to UTC for those Chinese and Japanese events that were listed in the Utsu catalogue by local time.

Our list contains a total of 2795 reports on fatalities due to earthquakes. Of these, 1393 are from Utsu only (2017, published plus personal communication), 868 are from NOAA only, 236 are from GRC only, 91 are from INGV only, three are from Musson (2001), one is from Wikipedia, and the remaining 203 are from two sources each.

Of all 248 countries, dependencies and other areas in the world (Worldometers 2022 -https://www.worldometers.info/united-nations/), for brevity simply referred to as 'countries' in the rest of the text, 117 have reported fatal earthquakes. The country associated with a report was determined as the closest one according to the Database of Global Administrative Areas (GADM 2022) level 0 administrative divisions version 3.6, based on the earthquake epicenter's coordinates.

Possibly duplicated events had been listed and marked as such by Utsu (2002). In these cases, only the event was included for which independent evidence could be found that it existed. In general, all fatalities due to an earthquake are attributed to a single country, although in cases where we have fatality information by country, we split the information into multiple entries, such as for the Aegean Sea earthquake on October 30, 2020, which caused fatalities in Turkey and in Greece.

The catalog we present does not contain events for which tsunamis were listed as a major cause of fatalities. We chose to focus on those earthquakes for which the collapse of buildings was the main cause of deaths. Fatalities caused by landslides, fire, and liquefaction could not be separated for the majority of earthquakes. Because only recent

studies attribute specific numbers of fatalities to these sources, we used total sums of fatalities in all cases.

The time covered is 856 BC to March 2022. The area covered is the world and the numbers of fatalities per event ranges from 1 to 830,000. There is no guarantee that all known occurrences of fatal earthquakes are found in the list. Also, the parameters are often not precise, especially those of early historical events. In Fig. 1, the numbers of reported fatalities for each earthquake are plotted as a function of time.

Updating the catalogue of fatal earthquakes, based on input by individual countries, would be desirable, but is not possible because the scope is too large for the present publication. However, we have data for Italy and Greece that we added. The list for Italian fatal earthquakes for the period 51 AD to 1990 was given to us by Gianfranco Vannucci (Personal communication 2022). Hypocenters and magnitudes of events in this catalog are not specified. Therefore, we used the source parameters from Guidoboni et al. (2018, 2019).

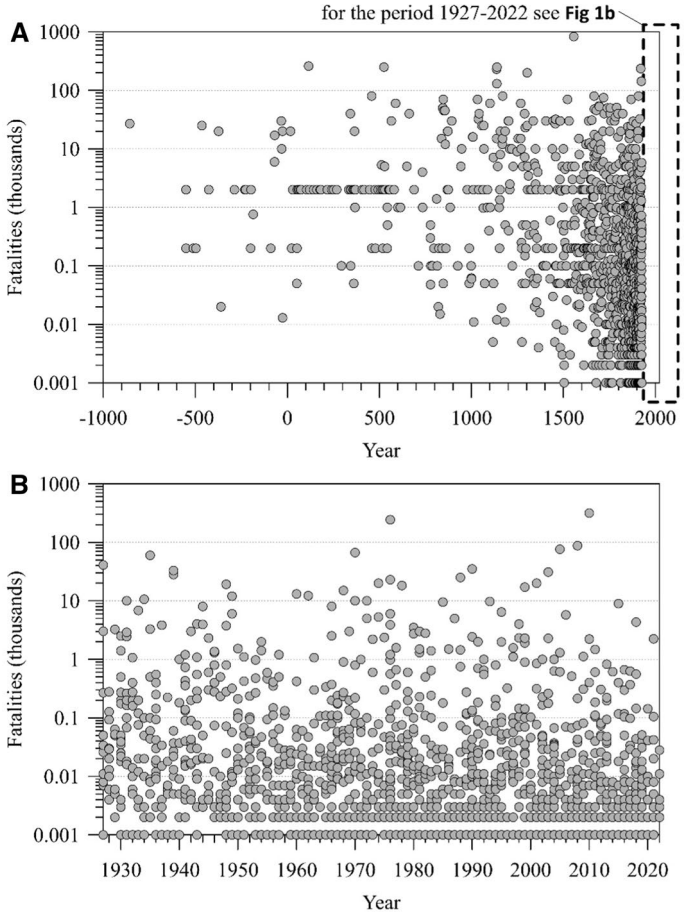

Fig. 1 Fatalities reported for each earthquake as a function of time. During early times (Fig. 1a), ranges of numbers were used by INGV because they are uncertain. We used the averages of these ranges: 5, 50, 500, and 5000

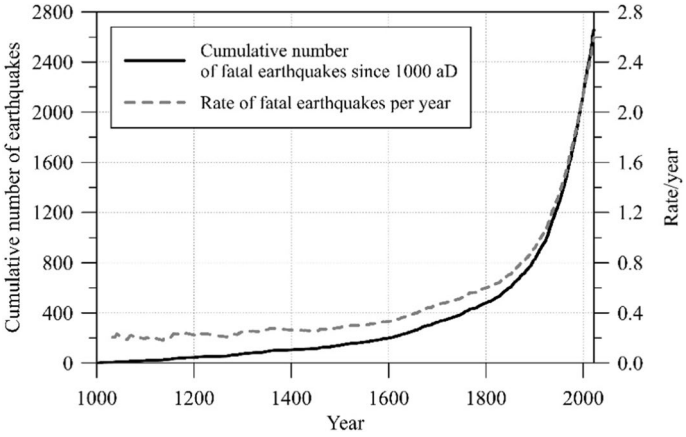

Fig. 2 Cumulative number of earthquake fatality reports as a function of the date (solid line) and the rate of reporting (dashed line). Both are low and approximately constant until 1600, where an increase can be noticed. Additional points of increase occur approximately in 1826, 1927, and 1965, after which year the reporting continues at an almost constant rate

Table 1 Estimated periods with approximately constant reporting rates of earthquake fatalities, with the number of reports in each period and the rate of reporting per year

Period	Number	Rate per year
1000 through 1600	200	0.33
1601 through 1825	329	1.46
1826 through 1926	484	4.79
1927 through 1964	454	11.95
1965 through 2022	1193	20.84

The current rate of reported fatal earthquakes is almost two per month. However, for earthquakes with the number of fatalities being larger than 16, the rate of reporting did not change in 1965; it has remained constant since 1927.

3 Rate of reports of fatal earthquakes

The cumulative number of reports is shown in Fig. 2 (solid line) as a function of time. Before the year 1000, the reporting is so low that it is not shown in this figure. After that date, the slope increases in increments with different reporting rates remaining approximately unchanged for some time. The times of change can be identified approximately. Suggested points of reporting rate increase are shown in Table 1, with the estimated reporting rate for each period (dashed line in Fig. 2). In the most recent period, a fatal earthquake is reported every 18 days.

4 The numbers of earthquake fatalities reported

The total number of fatalities reported reaches more than 8.3 million (Fig. 3). The largest number of fatalities occurred on 23 January 1556 in Shanxi, China, where more than 800,000 people died (Fig. 1). Utsu states that this “death toll is based on the number of bodies whose names were identified”.

The sum of reported fatalities (Fig. 3) becomes increasingly steep with time. Some steps are seen in this curve, due to earthquakes that produced great numbers of dead, such as the event in 1556. However, overall the curve is fairly smooth, especially in modern times (from 1927 onwards, as explained below), suggesting a constant occurrence of fatal earthquakes. Figure 4 shows that the cumulative sum of reported fatalities over the past 1800 years can be roughly approximated by an exponential.

The distribution of reports as a function of the order of magnitude of fatalities is shown for two periods in Table 2 (columns two and three), and column four lists the rate during the period covered by modern reporting (1927–2022).

5 Earthquake fatalities by country

China leads the list of fatalities (Online Appendix B) with about 2.3 million people lost, a factor of approximately 1.5 ahead of Turkey, the next country in the list, followed by Iran. These countries have reported more than 0.8 million dead each. The percent of countries in the world that have reported more fatalities than a given minimum number is shown in Table 3. For 1% of countries, more than 1 million earthquake fatalities have been reported, and for about 47% at least 1 fatality has been reported. If one considers those countries with more than 100 reported fatalities as having an earthquake problem, one finds that 31% qualify.

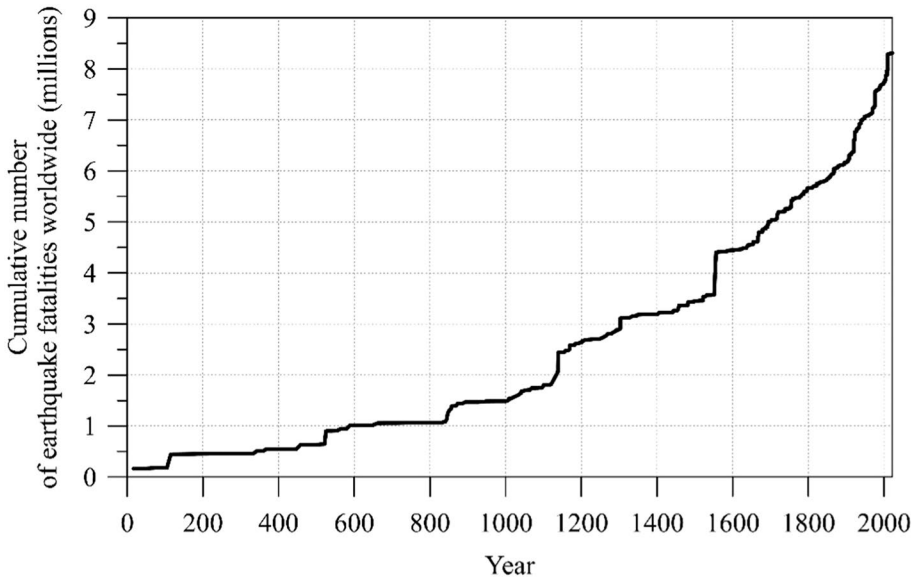

Fig. 3 The sum of reported fatalities as a function of date shows the rapid increase in earthquake fatalities with time, reaching over 8.3 million currently

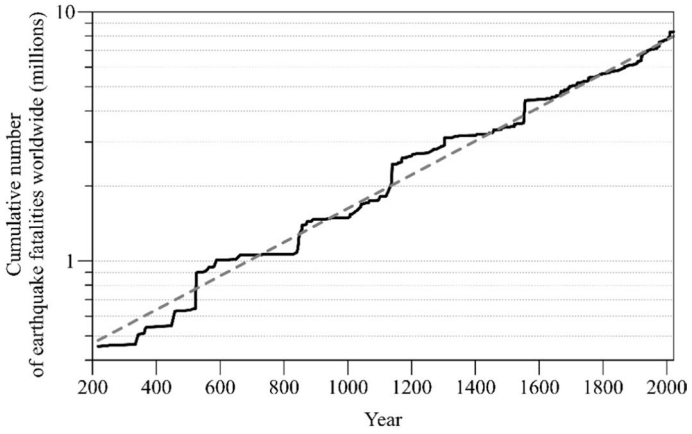

Fig. 4 The sum of reported fatalities as a function of date, in logarithmic scale. The dashed line represents an exponential trend over the past 1800 years

Table 2 Distribution of fatality counts as a function of size category for the entire catalog in column two and for the modern period in column three

Range of numbers of fatalities	Number of total earthquakes	Number in period 1927–2022	Rate per year 1927–2022
100,000–1,000,000	11	2	0.02
50,000–999,999	23	4	0.04
10,000–49,999	116	20	0.21
1000–9999	326	74	0.79
100–999	458	166	1.76
10–99	687	408	4.33
1–9	1174	973	10.32

The last column gives the rate of reports as a function of fatality range for the modern period

Table 3 Percent of all countries in the world as a function of the minimum reported number of fatalities for all times

Minimum fatalities	Percent of all countries
1,000,000	1
100,000	5
10,000	16
1000	22
100	31
10	40
1	47

If one considers that countries with a record of more than 100 reported earthquake fatalities have an earthquake problem, then 31% are in this category

6 Locations of fatal earthquakes

The maps in Fig. 5 show the epicenters of fatal earthquakes. They are grouped in three categories of degree of the disaster. The maps show that the margins of tectonic plates are peppered with fatal earthquakes, where they are densely populated. Along plate margins where few people live, such as the Aleutian and Kurile islands, even the greatest magnitude earthquakes cause few fatalities. When plate margins are located far offshore populated coasts, such as in Indonesia and western South America, the deaths counts in earthquakes are not very large, but frequent.

The truly great earthquake disasters occur in continental areas where stress is released along ruptures of long faults in the vicinity of population centers (Fig. 5a). Subduction zone earthquakes have some of the longest ruptures and largest magnitudes, but because of their distance from land the accelerations in the populated areas is relatively low. Also, in subduction zone earthquakes tsunamis are major sources of fatalities, but are not included in this report. This is why China, Turkey and Iran, and not coastal countries, are at the top of the list of countries in number of earthquake fatalities (Online Appendix B).

Although large portions of the globe are mostly devoid of earthquake disasters, such as Australia, northern Eurasia, Africa, and parts of North America, small counts of earthquake fatalities can nevertheless be noticed there also (Fig. 5c).

7 Potency of earthquakes

We define the parameter "earthquake potency", called potency for short in the following, as the number of fatalities divided by the number of earthquakes that generated them (Table 4 for all times). That is the average size of earthquake disasters in units of fatalities per country. Instead of using all reports, one might use only reports from the period of high-quality reporting (from 1927 onward, Table 5), but in that case the record is very short.

The ranking of countries by potency (Tables 4, 5 and Fig. 6) rearranges the sequence from that in Online Appendix B, which is ordered by the sum of reported fatalities in each country. The high potency of the first 10 countries in Table 4 is due to the fact that these countries experienced few fatal earthquakes, but major disasters.

The two main factors controlling potency are the length of ruptures and the proximity to population centres. Relatively small earthquakes that rupture across a population centre move countries upward in the ranking according to potency. Also, weak construction of buildings leads to high potency because, at a given level of shaking intensity, more structures collapse than average. Finally, overestimated numbers of fatalities lead to apparent high potency, an error that may afflict ancient earthquake reports. In eight of the 10 top rated countries in Table 4 and Fig. 6a, the high fatality numbers stem from reports before the year 1000 (Fig. 1, Online Appendix A), which renders them suspect. Finally, intentional inflation of numbers of fatalities in individual events can also falsify potency estimates.

A different view of potency presents itself, when one considers earthquake disasters during the period 1927 to March 2022, the modern period of reporting (Table 5, Fig. 6b). This period of 95 years is far shorter than earthquake return times, thus

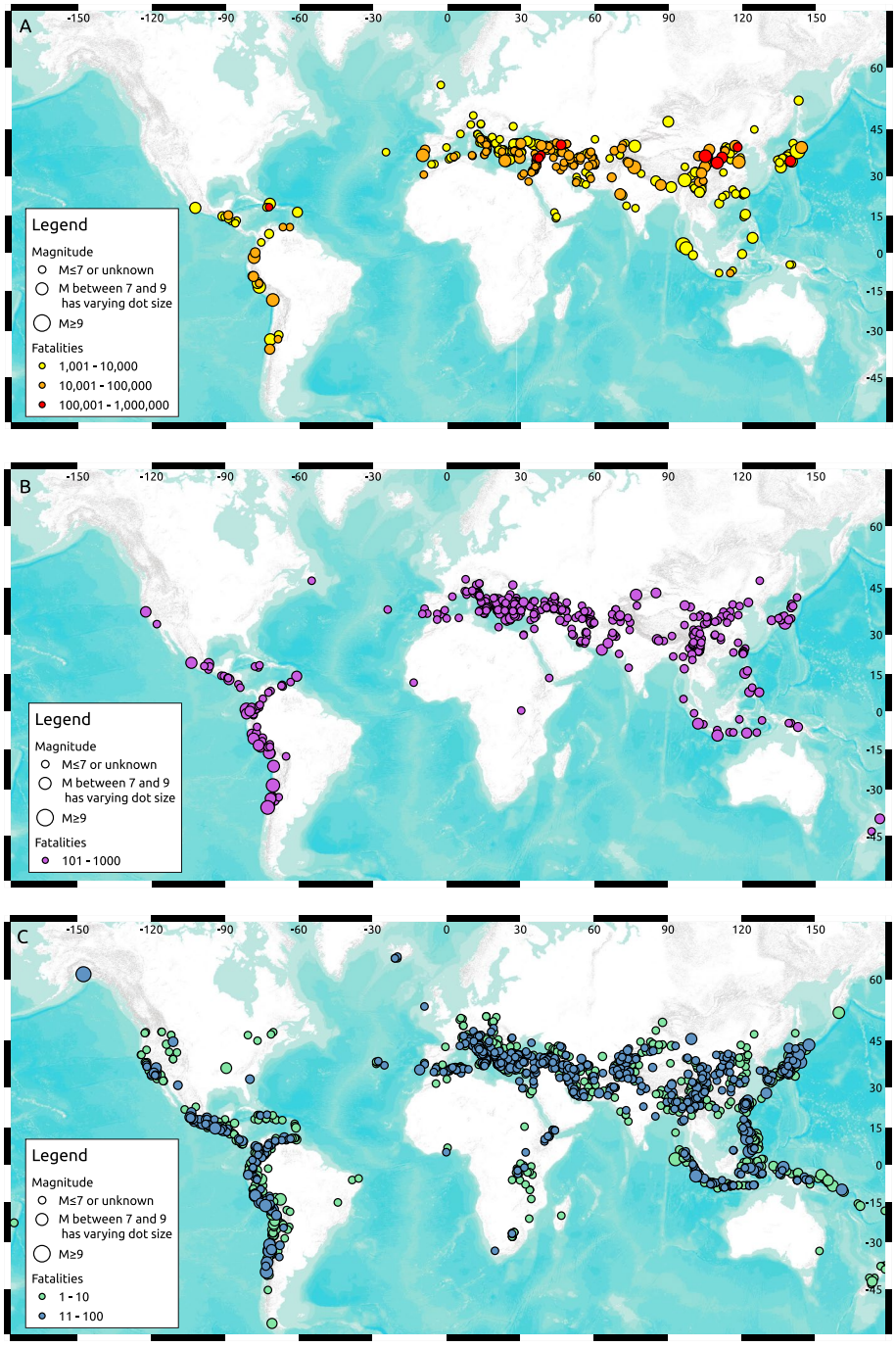

Fig. 5 Maps of fatal earthquakes with (**a**) 1000 and more, (**b**) between 100 and 999, (**c**) 1–99, fatalities, respectively. The size of the circles are proportional to earthquake magnitude, and the color indicates the number of fatalities

Table 4 Ranking of countries by potency, the average number of fatalities produced by an earthquake for all time

Rank	Country	Potency	Rank	Country	Potency	Rank	Country	Potency	Rank	Country	Potency
1	Haiti	40,410	31	Chile	1055	61	Switzerland	102	89	Malaysia	10
2	Azerbaijan	30,665	32	Peru	1015	62	Ireland	100	92	Australia	9
3	Syria	29,286	33	Greece	1001	62	Jordan	100	92	Solomon Islands	9
4	Israel	26,000	34	Spain	930	64	Kazakhstan	86	94	Tanzania	6
5	Tunisia	16,004	35	Tajikistan	906	65	Uganda	71	95	South Africa	5
6	Lebanon	15,074	36	Saint Lucia	900	66	Costa Rica	64	96	Fiji	4
7	Iraq	14,367	37	Algeria	847	67	Canada	62	96	Malawi	4
8	Egypt	13,639	38	Croatia	717	68	Cyprus	61	96	Mozambique	4
9	Armenia	11,284	39	Yemen	692	69	Myanmar	60	96	Panama	4
10	Turkmenistan	6537	40	Guinea	643	70	Georgia	59	96	Puerto Rico	4
11	Turkey	6461	41	France	617	71	Ethiopia	55	96	Rwanda	4
12	China	5707	42	Albania	549	72	South Korea	50	102	Burundi	3
13	Portugal	5551	43	Germany	505	73	Bangladesh	48	102	Dominican Rep	3
14	Uzbekistan	5253	44	Jamaica	461	74	New Zealand	42	102	Poland	3
15	Palestine	5072	45	Romania	440	75	Hungary	32	102	Vanuatu	3
16	Pakistan	4151	46	Colombia	376	76	South Sudan	31	106	Czech Republic	2
17	Ecuador	4093	47	El Salvador	314	77	Bolivia	30	106	Djibouti	2
18	Iran	3863	48	Afghanistan	306	77	Mongolia	30	106	Madagascar	2
19	Slovenia	2502	49	Libya	300	77	Slovakia	30	106	Serbia	2
20	Morocco	2480	50	North Macedonia	289	80	United States	26	106	Sudan	2
21	Nepal	2423	51	Indonesia	281	81	Austria	20	111	Belgium	1
22	Nicaragua	2110	52	Philippines	263	82	Papua N. Guinea	19	111	Brazil	1
23	Argentina	1899	53	Russia	206	83	Cuba	18	111	Kenya	1
24	Japan	1870	54	Taiwan	198	83	Honduras	18	111	Kosovo	1
25	Italy	1745	55	Martinique	196	85	Bosnia Herzegovina	17	111	Thailand	1
26	Guadeloupe	1669	56	Mexico	187	86	Ghana	12	111	Tonga	1
27	Venezuela	1483	57	Montenegro	129	87	Bhutan	11	111	Trinidad & Tobago	1
28	India	1470	58	Bulgaria	129	87	Ukraine	11			
29	United Kingdom	1400	59	Kyrgyzstan	118	89	D.R. Congo	10			
30	Guatemala	1148	60	Eritrea	106	89	Iceland	10			

Table 5 Potency27 estimates based on the record of fatal earthquakes since 1927, the modern period of reporting

Rank	Country	Potency	Rank	Country	Potency	Rank	Country	Potency	Rank	Country	Potency
1	Haiti	45,469	28	Russia	225	55	Honduras	18	80	Croatia	3
2	Armenia	9463	29	Mexico	213	56	Bosnia and Herzegovina	17	80	Poland	3
3	Turkmenistan	6537	30	Indonesia	205	57	Costa Rica	15	80	Vanuatu	3
4	Pakistan	4635	31	Lebanon	148	57	Cyprus	15	85	Azerbaijan	2
5	Morocco	2747	32	Colombia	141	59	Uzbekistan	14	85	Canada	2
6	Nepal	2663	33	Montenegro	129	60	Tunisia	13	85	Czech Republic	2
7	Nicaragua	2492	34	Taiwan	119	61	United States	12	85	Djibouti	2
8	China	1938	35	Egypt	117	62	Bhutan	11	85	Dominican Republic	2
9	Yemen	1337	36	Italy	115	62	Ukraine	11	85	Hungary	2
10	Guatemala	1287	37	Philippines	111	64	D.R. Congo	10	85	Jamaica	2
11	Tajikistan	1042	38	Uganda	71	64	Malaysia	10	85	Madagascar	2
12	Iran	1011	39	Bulgaria	65	66	Australia	9	85	Serbia	2
13	India	988	40	New Zealand	57	66	Solomon Islands	9	85	Sudan	2
14	Peru	970	41	Kyrgyzstan	54	68	Cuba	8	95	Belgium	1
15	Turkey	753	42	Myanmar	42	68	Spain	8	95	Brazil	1
16	Argentina	683	43	Ethiopia	35	70	Tanzania	6	95	Guadeloupe	1
17	Chile	655	44	Greece	33	71	Kazakhstan	5	95	Kenya	1
18	Guinea	643	44	Venezuela	33	71	South Africa	5	95	Kosovo	1
19	Ecuador	521	46	South Sudan	31	73	Fiji	4	95	Martinique	1
20	Romania	520	47	Bolivia	30	73	France	4	95	Slovenia	1
21	North Macedonia	312	47	Georgia	30	73	Malawi	4	95	South Korea	1
22	El Salvador	309	47	Mongolia	30	73	Mozambique	4	95	Thailand	1
23	Afghanistan	301	50	Albania	25	73	Panama	4	95	Tonga	1
24	Libya	300	51	Portugal	23	73	Puerto Rico	4	95	Trinidad & Tobago	1
25	Japan	296	52	Ghana	22	73	Rwanda	4			
26	Palestina	268	53	Iraq	20	80	Bangladesh	3			
27	Algeria	252	54	Papua New Guinea	19	80	Burundi	3			

This list shows the amount of suffering in earthquake disasters by country, in relatively recent time

potency27 (i.e. potency since 1927) may be considered less representative than the potency calculated for all known earthquake fatalities as shown in Table 4. Potency27, listed in Table 5, could be considered a measure of the average extent of recent earthquake disasters by country.

8 Discussion

The NOAA data set of earthquake fatalities seems to be the most useful source for current events, and combined with the corrected data from Utsu (2002) plus regional data from Greece and Italy make perhaps the best list of fatal earthquakes available. Several earthquakes that resulted in large numbers of fatalities were not contained in some of the catalogues, thus merging the catalogues was necessary (Online Appendix A).

Our catalogue contains 2795 earthquakes showing an increasing reporting rate as a function of time (Fig. 2). Among the times of substantial rate increases that of the year 1927 might be the most significant. After this year the reporting rate increases only in 1965 for earthquakes with fewer than 17 fatalities. This is about the same time when the US Geological Survey's world earthquake catalogues increased in quality. Given the fact that reporting for earthquakes with more than 17 fatalities remained constant since 1927, we define the period since 1927 as the modern period of reporting earthquake fatalities. During this period, the reporting seems to be uniform in all countries, whereas in early history great differences existed: In countries with highly developed cultures, such as Greece, China, Italy and Japan, records might be complete for earthquakes with significant numbers of fatalities even early on, whereas in many countries no records exist for early periods.

The strain accumulation rate due to plate motions worldwide is approximately constant in time, although different in different parts of the world. The strain release, however, occurs in sudden ruptures of faults locally, and kills people virtually instantly. Therefore, one might expect that steps should dominate the cumulative curve of reported fatalities (Figs. 3, 4). This is not the case over all time (Fig. 1). Although about five steps in more than 2000 years are apparent in Fig. 3, long periods, including the modern one, show approximately uniform accumulation of fatalities. This can be interpreted to indicate that on average over the entire Earth, medium size earthquake disasters happen at a steady rate, interrupted by occasional giant earthquake disasters.

Out of 248 countries in the world, there are 117 countries listed for which at least one earthquake fatality has been reported (Online Appendix A). This constitutes about 47% of all countries. The countries for which 100 or more fatalities have been reported over time number 77 (Online Appendix B), which is about 31% of all countries (Table 3). The events of greatest interest are those with more than 1000 fatalities, which occurred in 52 countries (Online Appendix B), 22% of all (Table 3).

The upward trend of the number of reports of deadly earthquakes (Fig. 2) is expected for the following reasons: (1) Record keeping has improved with time. (2) Communication from remote areas to governments has become possible. (3) The population has increased. On the other hand, resistance of buildings to shaking has improved, to different degrees in different countries, therefore, as a function of time, fewer houses collapse and thus fewer people are killed in earthquakes. The observation that the number of reports for earthquakes having caused fewer than 17 deaths increased in 1965 is interpreted as being due to better communication and record keeping.

The number of reports of fatal earthquakes is listed for each country in Online Appendix B, along with the sum of the number of fatalities (Fig. 7a, b for the periods 856 BC to 2022 and 1927–2022, respectively). The relationship between these two parameters is controlled by the local population density, the vulnerability of the built environment and the size of earthquake ruptures. The three countries with the highest numbers of fatalities, China, Turkey, and Iran, also suffered large numbers of fatal earthquakes (Online Appendix B and Fig. 7). However, some countries have reported large numbers of fatalities, but

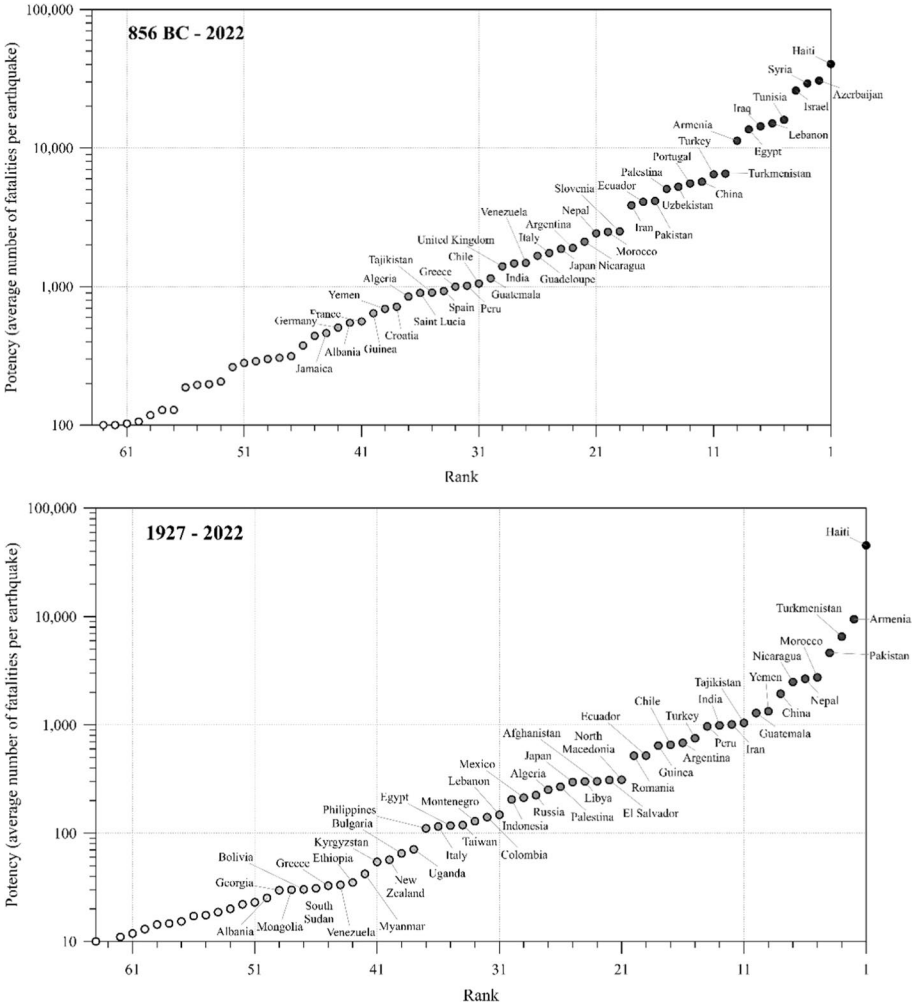

Fig. 6 Potency as a function of rank for earthquakes with Potency ≥ 100 fatalities for the period 856 BC to 2022 shown above, and the modern reporting period of 1927–2022 with Potency > 10 shown below

few fatal earthquakes, such as Syria, Azerbaijan, Haiti, Iraq, and Turkmenistan, for example (Fig. 7). In these countries, single large earthquake disasters dominate the reporting.

The number of reports is large in some countries that suffered relatively few fatalities, considering their unusually long reporting history, such as Italy, Japan, and Greece (Online Appendix B). In these countries, fatal earthquakes are generated by relatively short ruptures, which means that many events are needed to accumulate fatalities. In some countries, like Greece and Japan, higher than average building quality may contribute to fewer fatalities per fatal earthquake, on average. Earthquakes that generated major reported tsunamis, common in Chile, Indonesia and Japan, are not considered in this publication.

The existence of earthquake fatalities is unexpected in some regions. From the distribution of world seismicity, and locations of major plate boundaries, one might expect more

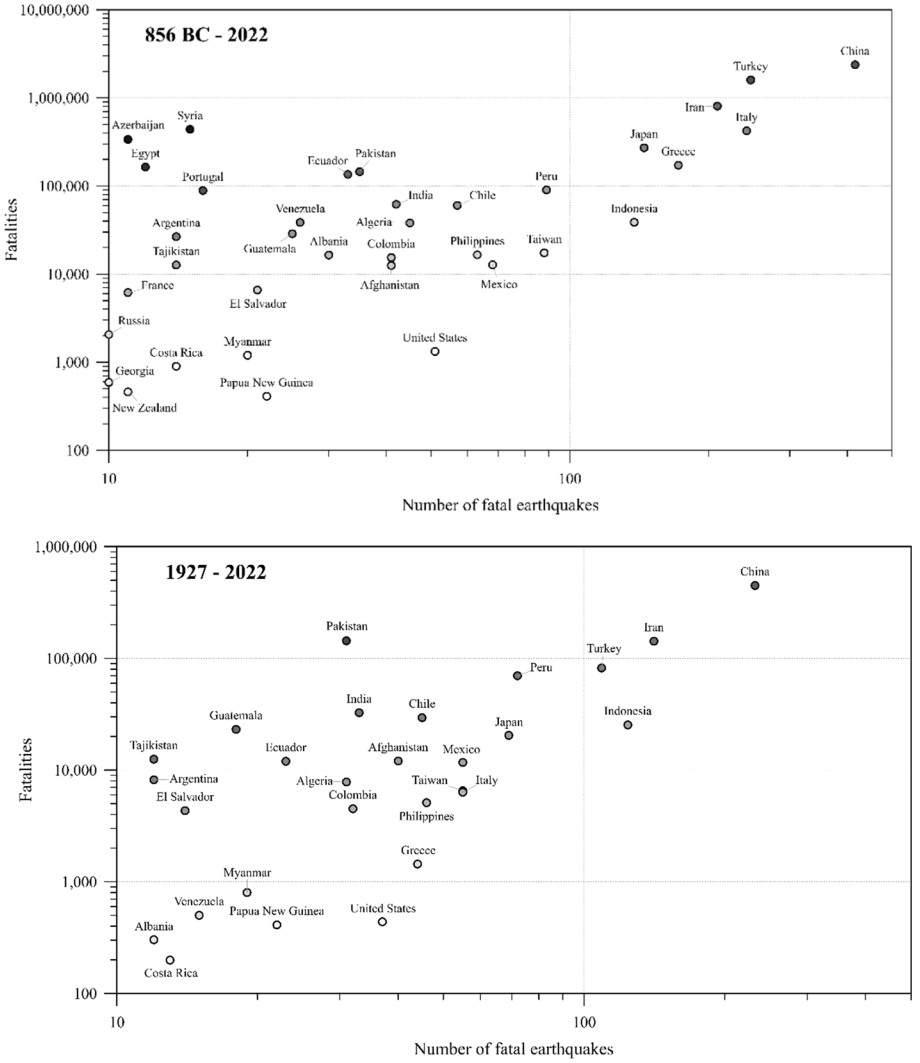

Fig. 7 Fatalities as a function of the number of fatal earthquakes by country, for the entire period of records, 856 BC to 2022 shown above and the modern recording period 1927–2022 shown below

earthquake fatalities in some areas than in others. This is generally true, but there are some exceptions.

India ranks low on the list of number of fatalities (Online Appendix B), although some of the world's greatest thrust earthquakes occur along the populated Himalayan megathrust. The approximate magnitudes and extent of several historic great ruptures in this area are known, but the numbers of fatalities they have cause are unknown. Most likely India will move near the top of a future list of earthquake fatalities.

The East African Rift earthquakes have generated only small numbers of fatalities, to date. From Fig. 5a, b one would not know that this plate boundary exists because no large

Table 6 Minimum magnitude earthquakes that have killed a given number, using data from 1960 onward, when *M* was measured instrumentally, worldwide

Minimum magnitude	Number killed
3.2	1
4.3	10
4.9	100
5.4	1000
5.7	10,000
7.0	100,000

and only one medium cases of earthquake fatalities are known there. Only a string of small earthquake disasters outlines the East African Rift (Fig. 5c). The absence of major earthquake disasters may be due in part to the short history of the region and by the relatively recent appearance of large buildings using heavy materials for construction.

Regions in which fatalities due to earthquakes are not expected, but have suffered substantial disasters include the United Kingdom, Newfoundland, Ireland and Guinea (Fig. 5, Online Appendix B). Other regions with minor seismic activity that have reported substantial earthquake losses include France, Germany and Switzerland. Part of the reason for this may be their relative high population density.

Iraq ranks high on the list of earthquake fatalities (Online Appendix B), but since the year 1100, only few events, all with minor casualty numbers (Online Appendix A), have been reported. The reason for this high ranking is large fatality numbers reported for historic events that occurred before the year 1008 (Online Appendix A), which is impossible to verify. Perhaps the high population density in early historic cultures in this region, along with poorly built brick buildings may have been responsible for major earthquake disasters, if they really did occurred.

The maximum number killed by small earthquakes is astonishing. Rock bursts reported globally in underground mines with $1.6 \leq M \leq 5$ have killed between 1 and 15 people each (our list imported from the cited sources in Online Appendix A is incomplete). These events do not fall into the category of fatal earthquakes reviewed in this paper and, therefore, are excluded from the following discussion.

The maximum number of fatalities for which an earthquake of a given magnitude is capable is listed in Table 6 (derived from Online Appendix B). The single smallest one, M3.2, occurred in Nepal, and killed one person. Three of the fatal earthquakes with $M \leq 4.1$ were associated with volcanoes, and one triggered a deadly avalanche. Two earthquakes of M3.8 and M3.9 occurred after the year 2000 (a time of comprehensive reporting) in Turkey and India, thus can be accepted as among the smallest killer earthquakes.

These earthquakes are exceptions. They have occurred in countries with weak construction techniques not able to resist much shaking, but heavy enough to kill inhabitants. Far more earthquakes of larger magnitudes have killed fewer. We conclude that earthquakes with approximately $M < 5$ kill people only under exceptional circumstances. However, it is important to realize that small magnitude earthquakes can kill, when buildings are inadequately constructed.

9 Conclusions

The combination of the earthquake fatality catalogues of NOAA, Utsu (2002), GRC and INVG leads to a more complete record from 856 BC to March 2022, than known before (Online Appendix A). This catalog demonstrates that the number of fatal earthquakes reported increases with time, ending in approximately constant reporting rate for earthquakes with fatalities larger than 17 since about 1927. The sum of all known fatality reports is 8.3 million.

Earthquake fatalities have been reported from 117 countries out of 195 worldwide. (Online Appendix B). Those countries that have reported more than 100 and more than 1,000 fatalities, number 77, and 52, respectively. The number of fatal earthquakes per country ranges from 1 to 416. Although the reporting history is vastly different in different countries, and one cannot compare them directly, we have prepared a ranking according to number of fatalities reported per country (Online Appendix B). China, Turkey, and Iran are leading this list of numbers of fatalities.

The potency of earthquakes in each country, we define as the sum of fatalities reported divided by the number of earthquakes that generated the associated disasters. Thus, the potency measures the size of the disaster generated by an average fatal earthquake in each country (Table 4). This value may be useful for earthquake disaster response planning.

The leaders in the list of potency are Haiti, Azerbaijan, Syria and Israel, all with potencies above 20,000 fatalities per average earthquake (Table 4, Fig. 6). None of these countries is strongly seismic, but when an earthquake disaster happens, it is major, if the record is correct. Early historic earthquakes influence the estimate of potency, but may not be recorded accurately.

The intervals between large fatal earthquakes are typically up to an order of magnitude larger than the 95 years of modern reporting. Therefore, many countries with significant earthquake disaster potential have not reached a realistic ranking in the lists of both Online Appendix B and Table 4. India is an example of this. It ranks 18th and 28th in the two lists, respectively, but the geodetically measured strain accumulation [e.g. (Bilham and Hough 2006)] and paleoseismology [e.g. (Wesnousky et al. 2017; Khattri 1987)] show that great ruptures generating large disasters along the Himalaya megathrust will happen in the future. Thus, the potency value currently available for India is underestimated. Similarly, the potency in countries with rare earthquakes is likely overestimated. The potency value is meaningful for countries with many fatal earthquakes.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11069-022-05627-x.

Acknowledgements We thank G. Vannucci for the data on Italian fatal earthquakes, R. Bishop and the reviewers for helpful suggestions.

Funding No funds, grants, or other support was received. The authors have no financial or proprietary interests in any material discussed in this article.

Data availablity The Appendices and Tables are available at http://fatal-earthquakes.icesfoundation.org.

Declarations

Conflict of interest The authors have not disclosed any competing interests.

References

Bilham R, Hough S (2006) Future earthquakes on the Indian subcontinent: inevitable hazard, preventable risk. South Asian J 12:1–9

Farahbod AM, Wyss M (2021) Help for injured people in the M7.3 Kermanshah earthquake of 12 November 2017 Iran. Am J Disaster Med 16:49–57. https://doi.org/10.5055/ajdm.2021.0386

GADM (2022) Database of global administrative areas. https://gadm.org/download_world36.html

Guidoboni E, Ferrari G, Mariotti D, Comastri A, Tarabusi G, Sgattoni G and Valensise G (2018) CFTI5Med, Catalogo dei Forti Terremoti in Italia (461 a.C.-1997) e nell'area Mediterranea (760 a.C.-1500) https://doi.org/10.6092/ingv.it-cfti5

Guidoboni E, Ferrari G, Tarabusi G, Sgattoni G, Comastri A, Mariotti D, Ciuccarelli C, Bianchi MG, Valensise G (2019) CFTI5Med the new release of the catalogue of strong earthquakes in Italy and in the Mediterranean area. Sci Data. https://doi.org/10.1038/s41597-019-0091-9

Khattri KN (1987) Great earthquakes, seismicity gaps and potential for earthquakes along the Himalayan plate boundary. Tectonophysics 38:79–92

Musson R (2001) The ten deadliest earthquakes ever. 2022. http://www.earthquakes.bgs.ac.uk/archive/archive_collections/Deadly.ht

NOAA (2022) National Geophysical Data Center / World Data Service (NGDC/WDS): NCEI/WDS Global Significant Earthquake Database. NOAA https://doi.org/10.7289/V5TD9V7K

Papazachos BC and Papazachou K (2003) The earthquakes of Greece, in Greek, Editions Ziti, 3rd edition

Papazachos BC, Comninakis PE, Karakaisis GF, Karakostas BG, Papaioannou CA, Papazachos CB, Scordilis EM (2000) A catalogue of earthquakes in Greece and surrounding area for the period 550BC-1999. Publ Geophys Lab Univ Thessaloniki. 333

Utsu T (2002) A list of deadly earthquakes in the world: 1500–2000. In: Lee WK, Kanamori H, Jennings PC, Kisslinger C (eds) International handbook of earthquake engineering and seismology. Academic, Amsterdam, pp 691–717

Utsu T (2017) personal communication

Wesnousky SG, Kumahara Y, Chamlagain D, Pierce IK, Karki A, Gautam D (2017) Geological observations on large earthquakes along the Himalayan frontal fault near Kathmandu, Nepal. Earth Plan Sci Lett 457:366–375

Worldometers (2022) https://www.worldometers.info/united-nations/