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THE TOP 100 FATAL EARTHQUAKES: EXAMINING FATALITY RISK REDUCTION GLOBALLY WITH RESPECT TO SEISMIC CODE IMPLEMENTATION

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ABSTRACT

The residual risk left through existing buildings of low earthquake resistance, governs the level of safety of the citizens in the case of extreme events. Since 1900 there have been more than 2200 earthquakes that have caused loss of life around the world, but the 100 most fatal events have caused around 93% of the total life losses and are examined to learn lessons. Recent events in some countries with significantly lower death tolls than in the top 100 list of fatal events are also examined with respect to seismic code implementation in order to gain understanding on the empirical reduction of fatality risk through code implementation and adherence.

An updated global seismic code index has been proposed, examining the changes to all the countries since the worldwide seismic code index and building practice factor were published by Daniell et al. (2014). This has been built in conjunction with a compendium of casualty estimation methodologies globally. A presentation of global fatalities from earthquakes and the relative fatality risk compared to other death types was presented by Daniell et al. (2017). In this paper, by comparing the seismic code index (SCI), the top 100 events and F-N curves, a few initial examples are shown and the basis for further studies in the field of residual risk analysis for earthquake fatalities is provided.

Keywords: earthquake fatalities; F-N function; global; residual risk; seismic codes

1. INTRODUCTION

Since 1900 there have been more than 2200 fatal earthquakes around the world, causing the loss of around 2.3 million lives. The Top 100 fatal events have caused over 93% of the fatalities globally (2.14 million deaths). The event cut-off is around 1600 fatalities. This is an important statement, as we begin to realise the importance of building collapse prevention for major events hitting urban centers and the need to protect citizens against extreme events death tolls occurring. A large range of death toll estimates is present in the literature as shown by the global range of 1.45 million to 3.66 million for the top 100 events since 1900.

Over the past 15 years, the CATDAT database is constantly developed and maintained (Daniell et al., 2011), incorporating over 33,000 sources in 90 languages globally, to validate, estimate and check death tolls. This effort amalgamates many individual records, often showing a large range of quoted values for death tolls (both accurately and inaccurately). The Pomonis database of fatal earthquakes and consequences details many events with clear focus on the larger events with use within the GEMECD and other databases globally (Pomonis et al., 2009; So et al., 2012). The major focus within the database comes from investigating official and unofficial death tolls in some depth for big events where the official toll is not available or doubtful. The amalgamation of the two databases to arrive at a common joint list of the top 100 events has been undertaken with many discussions of events made over the last few years between Daniell and Pomonis and in the framework of this paper. This represents a significant step forward to hopefully rectify published errors.

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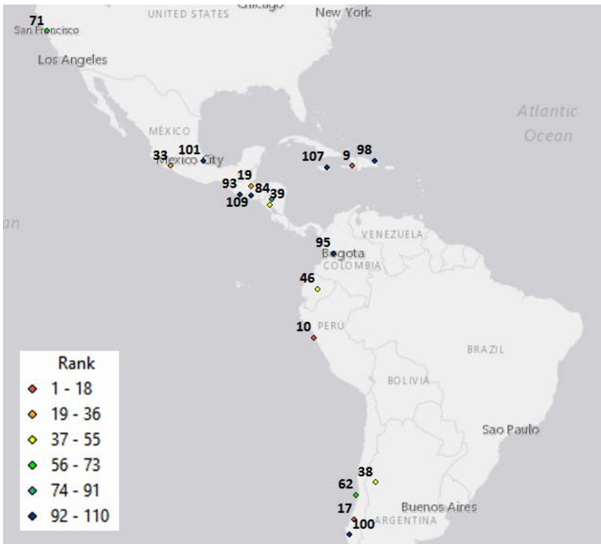
2. RECTIFYING THE TOP 100 EVENTS SINCE 1900

Many errors exist in databases currently around the world regarding earthquake fatalities. These have often been propagated by errors in the original databases such as OFDA in the case of the EM-DAT database, or simply not using updated values. In addition and especially for events prior to about 1995 (advent of the world wide web) there are often several possible death tolls per event (e.g. Utsu, 1990; Utsu, 2002) and furthermore some mega-death events (loss of life greater than 10,000) such as the 1948 Ashgabat, 1988 Armenia, 2010 Haiti, etc. for which uncertainty on the actual death toll is significant. By rectifying the top 100 events, we propose the preferred death toll and approximate % of deaths due to shaking (related to building collapse) for these historically most important events, as well as an upper and lower value (through the amalgamation of the databases and discussion). Also the “all literature” upper and lower values (not necessarily correct) are also shown (see Table 1). There are 34 countries primarily affected by these 100 events, plus a number of other countries also affected by damage or even loss of life (as indicated).

Of the Top 100 events, nearly 30% of the fatalities were caused by secondary hazards, reminding us of the need for better tsunami, landslide and fire prevention. In 11 of the Top-100 events the deaths were almost exclusively due to tsunami, in 3 events the majority of the deaths were due to landslides and related hazards and in 2 events they were overwhelmingly due to fire following. Large strides have been made since the 2004 Indian Ocean and the 2011 Tohoku earthquake and tsunami in characterizing, quantifying tsunami vulnerability and risk and give timely warnings of tsunamis. Nearly 59% of the global life losses since 1900 have occurred due to the top 10 events, with 43% of the joint fatalities of these 10 events caused by secondary hazards. It is interesting to note that only five of the Top-100 events occurred in Europe (bold and underlined), 4 in Italy and 1 in Romania with an additional 10 events in Turkey (bold). Also interesting is that from 1900-1958, 50 events in the top 100 events occurred which is obviously exactly the same as the 1959-2017 time period (50 events).



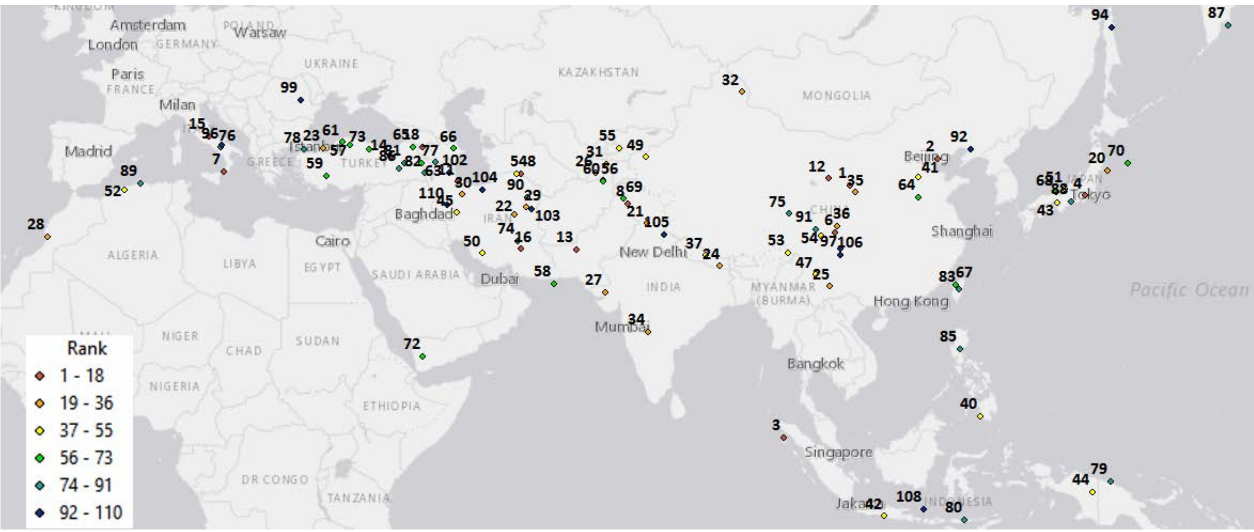


Figure 1. Locations of the top 100 events (and the 101-110th placed) ranked in descending order of fatalities.

Figure 1 shows the location of the Top-110 events with the index number on the map indicating their rank.

Table 1. The Top 100 fatal events since 1900 as created via the combined CATDAT, Pomonis database

Rank	**EQ Date**	**Mag.**	**Name**	**ISO_country**	**Preferred Toll**	**Approx. Shaking**	**Lower Pref.**	**Upper Pref.**	**Global Lower**	**Global Upper**
1	16/12/1920	Mw8.3	Haiyuan	CHN	273400	50.0%	273400	273400	100000	273400
2	27/07/1976	Mw7.6	Tangshan	CHN	242419	100.0%	240000	255000	240000	655237
3	26/12/2004	Mw9	Indian Ocean Tsunami	IDN, LKA, IND, THA etc.	228194	0.5%	227898	230100	227898	297248
4	1/09/1923	Mw7.9	Great Kanto	JPN	105385	10.5%	105385	143000	99331	143000
5	5/10/1948	Mw7.2	Ashgabat	TKM, IRN	100000	100.0%	33000	176000	10000	176000
6	12/05/2008	Mw7.9	Sichuan	CHN	88287	70.0%	88000	89000	69165	88287
7	**28/12/1908**	**Mw7.24**	**Messina**	**ITA**	**85926**	**97.0%**	**80000**	**90000**	**46869**	**200000**
8	8/10/2005	Mw7.6	Kashmir	PAK, IND, AFG	81000	67.3%	74648	87367	60361	87367
9	12/01/2010	Mw7	Haiti	HTI	80000	100.0%	70000	167082	46000	316000
10	31/05/1970	Mw7.9	Ancash	PER	66794	60.0%	52000	96794	52000	100000
11	20/06/1990	Mw7.4	Manjil-Rudbar	IRN, AZE	45000	99.0%	40000	50000	30000	50000
12	22/05/1927	Mw7.7	Gansu	CHN	41420	97.6%	40900	45000	35495	200000
13	30/05/1935	Mw8.1	Quetta	PAK	40000	99.0%	40000	50000	15000	70000
14	**26/12/1939**	**Mw7.7**	**Erzincan**	**TUR**	**39035**	**84.5%**	**32968**	**45000**	**23149**	**45000**
15	**13/01/1915**	**Mw6.99**	**Avezzano**	**ITA**	**32610**	**100.0%**	**29978**	**35000**	**29978**	**35000**
16	26/12/2003	Mw6.6	Bam	IRN	31000	99.0%	26225	31000	26225	43000
17	25/01/1939	Mw7.7	Chillan	CHL	30000	99.5%	28000	30000	5685	30000
18	7/12/1988	Mw6.7	Spitak	ARM	25076	99.7%	25000	26000	25000	50000
19	4/02/1976	Mw7.5	Guatemala	GTM, SLV, HND, MEX	22778	99.0%	22400	23000	22368	23000
20	11/03/2011	Mw9	Tohoku	JPN	22152	17.1%	18450	22152	18450	22152
21	4/04/1905	Mw7.8	Kangra	IND	20000	95.0%	18815	20000	10600	27688
22	16/09/1978	Mw7.4	Tabas-e-Golban	IRN	19214	100.0%	18000	25000	15000	25000
23	**17/08/1999**	**Mw7.6**	**Izmit**	**TUR**	**17217**	**100.0%**	**17127**	**23000**	**17118**	**45000**
24	15/01/1934	Mw8	Bihar	NPL, IND	15772	99.3%	10700	15772	7253	15772
25	4/01/1970	Mw7.2	Tonghai	CHN	15621	95.0%	15000	20000	10000	15621
26	21/10/1907	Mw7.2	Karatag	TJK	14000	65.0%	12000	15000	200	40000
27	26/01/2001	Mw7.6	Bhuj	IND, PAK	13823	100.0%	13823	21004	13823	21004
28	29/02/1960	Mw5.7	Agadir	MAR	13100	100.0%	12000	15000	12000	20000
29	31/08/1968	Mw7.2	Great Dasht-e-Bayaz	IRN	12488	100.0%	12000	15000	7000	20000
30	1/09/1962	Ms6.9	Buyin-Zahra	IRN	12225	100.0%	12000	14000	10000	12225
31	10/07/1949	Mw7.6	Khait	TJK	12000	2.0%	7200	18000	3500	28000
32	10/08/1931	Mw7.9	Fuyun	CHN	10200	99.0%	10000	10200	300	10200
33	19/09/1985	Mw8	Mexico City	MEX	10153	99.0%	9500	10500	9500	10153
34	29/09/1993	Mw6.2	Latur-Osmanabad	IND	10050	100.0%	9748	11000	7601	11000
35	12/04/1921	Ml6.5	Ningxia	CHN	10000	90.0%	10000	10000	10000	10000
36	25/08/1933	Mw7.3	Diexi	CHN	9365	50.0%	6865	10000	2500	9365
37	25/04/2015	Mw7.8	Nepal	NPL	9055	94.5%	9055	9055	9055	9055
38	15/01/1944	Mw7.1	San Juan	ARG	8000	100.0%	8000	10000	1500	10000
39	23/12/1972	Ms6.2	Managua	NIC	7500	100.0%	5000	11000	4000	11000
40	16/08/1976	Mw8	Moro Gulf	PHL	7079	12.0%	7000	8000	3564	8000
41	22/03/1966	Mw6.8	Hebei	CHN	7064	100.0%	7000	7100	1000	8064
42	26/05/2006	Mw6.4	Java	IDN	6736	100.0%	6736	6736	5749	6736
43	16/01/1995	Mw6.9	Kobe	JPN	6433	75.0%	6000	6048	5502	6048
44	25/06/1976	Mw7.1	Irian Jaya	IDN	6000	8.0%	5400	9422	420	9422
45	23/01/1909	Ms7	Silakor	IRN	6000	100.0%	5500	8000	5000	8000
46	5/08/1949	Ml6.8	Ambato	ECU	6000	73.3%	5050	6000	4000	8000
47	16/03/1925	Ms7	Dali	CHN	5808	93.1%	5800	6500	3600	6500
48	1/05/1929	Mw7.1	Kopet-Dagh	TKM, IRN	5803	100.0%	3800	5803	3800	5803
49	22/08/1902	Mw7.7	Atushi	CHN	5653	91.2%	5000	6000	1750	8500
50	10/04/1972	Ms6.9	Qir	IRN	5374	99.1%	5374	5374	5054	5400

51	28/06/1948	Mw7	Fukui	JPN	5131	90.0%	3769	5390	3238	5570
52	10/10/1980	Mw7.1	El Asnam	DZA	4900	100.0%	2633	6500	2590	20000
53	15/08/1950	Mw8.6	Assam	IND, CHN	4826	70.0%	4826	6000	574	30000
54	24/03/1923	Mw7.2	Luhuo	CHN	4800	90.0%	4800	4800	3000	4800
55	16/12/1902	Ml6.4	Andizhan	UZB	4722	100.0%	4602	7000	700	20000
56	30/05/1998	Mw6.5	Badakhshan 2	AFG, TJK	4500	70.0%	4400	4700	4000	4700
57	**26/11/1943**	**Ms7.2**	**Ladik**	**TUR**	**4020**	**100.0%**	**4000**	**5000**	**2824**	**5000**
58	27/11/1945	Mw8	Makran	PAK, IRN	4000	7.5%	4000	4000	300	7000
59	**3/10/1914**	**Ms6.9**	**Burdur**	**TUR**	**4000**	**100.0%**	**4000**	**4000**	**300**	**4000**
60	4/02/1998	Mw5.9	Badakhshan 1	AFG	4000	82.8%	2323	4600	2323	4600
61	**1/02/1944**	**Ms7.2**	**Gerede**	**TUR**	**3959**	**100.0%**	**3959**	**5000**	**595**	**5000**
62	17/08/1906	Mw8.5	Valparaiso	CHL	3882	90.0%	1500	20000	1500	20000
63	**24/11/1976**	**Mw7**	**Muradiye**	**TUR, IRN**	**3840**	**100.0%**	**3626**	**5000**	**3626**	**10000**
64	31/07/1937	Ml6.9	Heze	CHN	3833	98.7%	3833	3833	390	3833
65	**28/04/1903**	**Mw7**	**Malazgirt**	**TUR**	**3560**	**100.0%**	**3500**	**5000**	**600**	**6186**
66	13/02/1902	Ml6.9	Shemakha	AZE, IRN	3500	100.0%	1714	5000	86	20000
67	20/04/1935	Ms7.1	Miaoli	TWN	3276	99.5%	3276	3276	3270	3276
68	7/03/1927	Mw7.1	Tango	JPN	3274	95.0%	2925	3274	2925	3274
69	28/12/1974	Ms6.2	Pattan	PAK	3150	100.0%	994	5300	700	5300
70	2/03/1933	Mw8.4	Sanriku-oki	JPN	3064	2.0%	3064	3064	3000	3064
71	18/04/1906	Mw7.9	San Francisco	USA	3000	40.0%	2000	3400	452	3400
72	13/12/1982	Mw6.2	Dhamar	YEM	3000	100.0%	2800	3000	1507	3000
73	**20/12/1942**	**Mw7.2**	**Erbaa**	**TUR**	**3000**	**100.0%**	**3000**	**3000**	**1000**	**4000**
74	28/07/1981	Mw7.2	Golbaf	IRN	3000	100.0%	2500	5000	1500	8000
75	13/04/2010	Mw6.9	Yushu	CHN	2968	100.0%	2698	2968	2220	10000
76	**23/11/1980**	**Mw6.89**	**Irpinia**	**ITA**	**2919**	**96.6%**	**2735**	**4689**	**2500**	**4689**
77	27/04/1931	Ms6.3	Zangezur	ARM, IRN	2890	98.3%	2890	2890	300	2890
78	**9/08/1912**	**Ms7.3**	**Saros-Marmara**	**TUR**	**2836**	**99.3%**	**2700**	**3000**	**216**	**3000**
79	17/07/1998	Mw7	Aitape	PNG	2683	0.0%	2683	2700	2683	2700
80	12/12/1992	Mw7.7	Flores	IDN	2519	0.0%	2500	2519	2080	2519
81	**19/08/1966**	**Mw6.8**	**Varto**	**TUR**	**2517**	**100.0%**	**2394**	**3000**	**2394**	**3000**
82	6/05/1930	Ms7.6	Salmas	IRN, TUR	2514	100.0%	1360	3000	1360	7000
83	20/09/1999	Mw7.6	Chi-Chi	TWN	2492	94.0%	2360	2492	2297	2492
84	31/03/1931	Ml5.6	Managua	NIC	2450	99.0%	2450	2450	1000	2500
85	16/07/1990	Mw7.7	Luzon	PHL	2430	79.8%	2430	2430	1621	2430
86	**6/09/1975**	**Ms6.7**	**Lice**	**TUR**	**2385**	**100.0%**	**2300**	**3000**	**2000**	**3000**
87	4/11/1952	Mw9	Kamchatka	RUS, USA	2336	0.0%	2336	2336	2336	10500
88	12/01/1945	Ms6.8	Mikawa	JPN	2306	100.0%	1961	2306	1180	2306
89	21/05/2003	Mw6.8	Boumerdes	DZA	2278	100.0%	2266	2278	2266	2278
90	25/05/1923	Ml5.7	Torbat	IRN	2219	100.0%	900	2219	300	5000
91	6/02/1973	Ml7.7	Luhuo	CHN	2199	100.0%	2175	2199	2175	2199
92	4/02/1975	Mw7	Haicheng	CHN, KOR	2041	65.1%	2041	2041	300	2041
93	19/04/1902	Mw7.5	Guatemala	GTM	2000	90.0%	200	2000	200	2000
94	27/05/1995	Mw7	Neftegorsk	RUS	1989	100.0%	1989	2068	1829	2068
95	25/01/1999	Mw6.1	Armenia	COL	1885	42.2%	1885	1885	1185	5785
96	**23/07/1930**	**Mw6.72**	**Vulture**	**ITA**	**1881**	**100.0%**	**1526**	**2200**	**1404**	**5000**
97	30/07/1917	Mw7.3	Daguan	CHN	1879	4.2%	1800	1879	1800	1879
98	4/08/1946	Mw7.9	Dominican Republic	DOM	1790	5.0%	1790	2550	105	2550
99	**4/03/1977**	**Mw7.5**	**Vrancea**	**ROM, BUL**	**1705**	**100.0%**	**1581**	**1705**	**1387**	**1705**
100	22/05/1960	Mw9.5	Valdivia	CHL, USA, JPN	1655	14.9%	1655	1800	1500	7231
TOT	**1900-2017**		**Global**		**2140212**	**70.3%**	**1959394**	**2513150**	**1453001**	**3639012**

A further ten events of note have been examined as their death toll was close to the cutoff of the top 100 at approximately 1650 people, given that the range in most of these often extends into the acceptable top 100, were the upper value to be used as the preferred death toll. The extensive literature for each of these additional earthquakes will not be included in this paper but are available upon request. The top 10 events, contribute just over 63% of the fatalities in the top 100 list. It is important to note that 3 of these occurred in China (the 1920 Haiyuan and 1976 Tangshan events causing jointly nearly 516,000 deaths). It can be seen that there is a large difference between the top 3 events and the next set of events. By far one of the events with the greatest unknowns is the Ashgabat (Turkmenistan) earthquake in 1948.

There are some events which need discussion as to the choice of number used in the death tolls. The Haiyuan earthquake (1) is often quoted wrongly in many publications (i.e. EM-DAT, MunichRe, etc.) given the 2010 publication upraising the death tolls (Zhang et al., 2010). This is also the case for the Great Kanto earthquake (4), where the commonly quoted 99,500 dead and 43,500 missing was reassessed in 2004 (Moroi and Takemura, 2004).

The 1948 earthquake in Turkmenistan (formerly Turkmen SSR) has had many published death toll estimates from 10,000 (Krumbach and other early authors) to 19,800 (Utsu) and 23,282 (official) and up to 110,000 (Golovkin, speech, 1973; Drumya and Shebalin, 1985), and 176,000 in the Turkmen Presidential Address, Turkmenistan Government (2007). It is an event where there is a clear order of magnitude between estimates as said by Nalivkin (1989). Nikonov (1998) stated at least 70,000 died without putting a cap on the death toll. For the purposes of the database this has been given a preferred value of 100,000.

The Messina earthquake of 1908 (7) holds the unenviable title of the worst European event in terms of deaths toll at 80,000 to 90,000. Building codes and seismic zonation have since been put in place, and events such as this at the turn of the 20th century shaped earthquake risk reduction efforts in Italy. The death toll of the Haiti earthquake in 2010 (9) from the Système National de Gestion des Risques et des Desastres (SNGRD) originally has been shown to be an overestimation in at least 7 publications investigating the Haiti death toll, and thus, this value has only been put into the global range, rather than the preferred range as discussed in Daniell et al. (2013), and Ambraseys and Bilham (2011). This event is one of the few which does not relate well with the official government estimate, with 80,000 being chosen as the median estimate (in rounded numbers to show the uncertainty).

Table 2. Haiti death tolls as reported by various post-disaster studies

Source	**Range (Lower to Upper)**
Haiti Government (SNGRD)	222,570 to 316,000
Kolbe et al. (2010) PaP	136,813 to 180,545
Melissen (2010)	52,000 to 92,000
Schwartz USAID Report (2011)	46,190 to 84,961
Garfield – Crowd Sourcing (2013)	60,000 to 80,000
Doocy – Population Based (2013)	63,061 to 86,555
Doocy – Building Damage Survey (2013)	49,033 to 81,862

The 1941 Andaman Islands event has been removed from the Top 100 database following studies from a number of authors including Martin & Szeliga (2010) in recent years mooting that an earthquake such as this could not have caused over 5,000 tsunami deaths in India at the time despite the findings of Murty (1984).

A number of Iranian earthquakes (2003 Bam, 1997 Ardebil, 1997 Ferdows, 1957 Farsinaj, 1957 Sangechal) as well as Turkish (1976 Caldiran, 1944 Bolu, 1942 Niksar-Erbaa, 1903 Malazgirt) and other events (i.e. 1998 Afghanistan, 1939 Chillan etc.) as detailed in Table 1 have the issue of an official death toll being lower than the unofficial death toll. In most cases the official death tolls are either an incomplete count due to incomplete search and rescue and body retrieval from the rubble or because prompt burials or cremations had taken place (e.g. 1991 Uttarkashi just below the Top-100 lost) as the official count requires bodies, or in other cases a local overestimate.

3. THE APPLICATION OF SEISMIC RESISTANT CODES RELATED TO THE TOP 100 EVENTS

In Table 3 we show seismic codes in application pre- and post- event occurrence for each of the top-100 lethal earthquakes. as well as a reference to the seismic zonation in the latest code of the respective region. Seismic resistant design codes have contributed greatly towards reducing life losses due to earthquakes in many countries, but only where a significant proportion of the stock is engineered (in design and execution) buildings and the code adherence level is high. In many cases, the percentage of the building stock that is deemed seismically resistant (low probability of collapse) is significantly smaller than first thought when looking at the expected number of buildings built since first codes were introduced (assuming 100% adherence). Seismic resistant design codes have been introduced in over 150 nations over the past 100 years. However, in many countries these codes are not adequately enforced, or have many exclusion clauses or are not compulsory. In addition, there is the problem of the existing buildings built according to outdated or prior to seismic safety regulations.

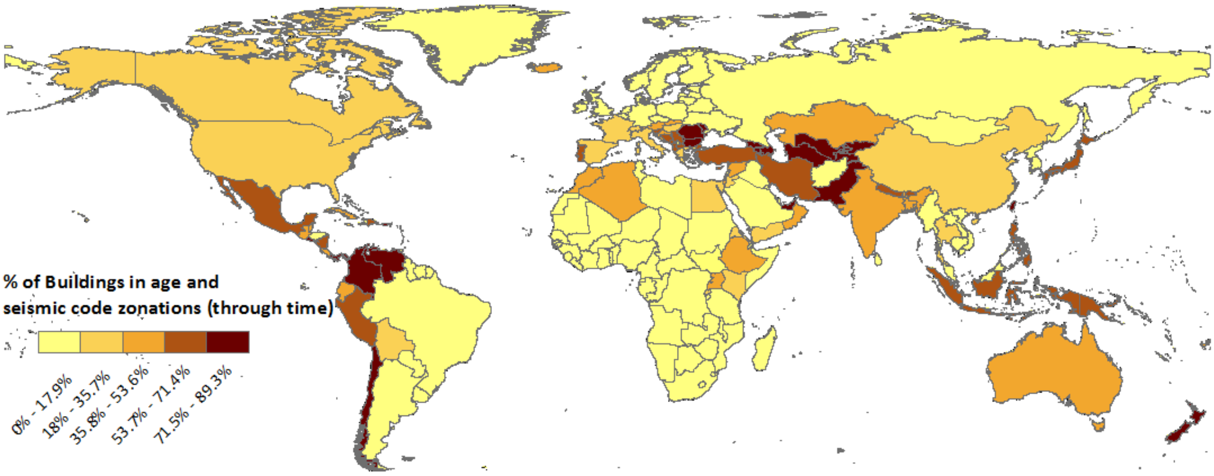


Figure 2. The percentage of buildings in each country that should have been built under a seismic resistant code (excluding small building provision)

In many countries the residual risk from existing buildings is significant even though code implementation is quite satisfactory, as the rate of replacement of older buildings can be rather slow. It is also often found that in some countries less than 1% of the buildings are built under an earthquake resistant code; meaning that general engineering practice and building types used are often more important when assessing the risk. In 46 of the top-100 events there was an earthquake resistant code in place at the time of the event, with 67 implemented within 25 years of the disaster occurring. The seismic code index (SCI) (Daniell et al. (2014)) was used to characterise the design codes, but many advances have been made recently which contribute to the reduction of potential future losses. For example, there has been constant improvement in code quality in three successive codes in El Salvador (Figure 3), with improvements as to the description of the building typologies, a better hazard zonation and being comparable with other codes in South America (Chavez et al., 2012). However, since 1997, updates to the housing and hospital codes were never legalised according to Flores (2016, pres). Future work will investigate the age of buildings within each of the 30+ countries affected by the top 100 earthquakes, code adherence levels and quality of construction to better quantify residual risk. Building typologies and the residual risk have also been covered by Tsang et al. (2017a, 2017b).

Figure 3. Left: 1966 code (21.01.1966); Middle: 1989 code (14.09.1989); Right: 1997 code in El Salvador

Table 3. Seismic codes pre- and post-

occurrence for each of the top-100 lethal earthquakes

Rank	EQ Date	Country	SCI	Pre	Post	Zonation Latest Code (main affected region)
1	16/12/1920	CHN	20			GB50011-2010(2016)
2	27/07/1976	CHN	35	1974 (TJ11)	1978 (TJ11)	GB50011-2010(2016)
3	26/12/2004	IDN	56	SNI–02-1726-2002	same	SNI 1726:2012
4	1/09/1923	JPN	36		1926 (after)	BSL-2016
5	5/10/1948	TKM	35	1935	1951	SNT 2.02.01.-98, 2.02.03.-04
6	12/05/2008	CHN	65	2001 (GB50011)	2010 (GB50011)	GB50011-2010(2016)
7	28/12/1908	ITA	28	Pre-1909	RD193/1909	NTC-2008
8	8/10/2005	PAK	35		2007 NESPAK	NESPAK: 2007
9	12/01/2010	HTI	30			None
10	31/05/1970	PER	29		1977	2016 (E-030, 079)
11	20/06/1990	IRN	65	1988-No. 2800	1999 - 2800	2800-05 BHRC:2015
12	22/05/1927	CHN	23			GB50011-2010(2016)
13	30/05/1935	PAK	20			NESPAK: 2007
14	26/12/1939	TUR	32		1940	TEC-2016
15	13/01/1915	ITA	30	RD193/1909	1916 (5/11)	NTC-2008
16	26/12/2003	IRN	75	1999 - 2800	2005 - 2800	2800-05 BHRC:2015
17	25/01/1939	CHL	35	1928	1963	NCh 433 Of.1996 Mod. 2009 + DS 61-2011
18	7/12/1988	ARM	67	1981	1995	RABC II-6.02-2006
19	4/02/1976	GTM	12		1996 NTDS	1996/2002 in 17/334 municipalities
20	11/03/2011	JPN	100	2001-BSL	BSL-2016	BSL-2016
21	4/04/1905	IND	20			BIS IS 1893:2014
22	16/09/1978	IRN	45	1969-1967 SC 519	1988	2800-05 BHRC:2015
23	17/08/1999	TUR	93	1997	TEC-2006	TEC-2016
24	15/01/1934	NPL	13			NBC105: 1994
25	4/01/1970	CHN	30		1974 (TJ11)	GB50011-2010(2016)
26	21/10/1907	TJK	19		1928	SNIP 22-07-2007
27	26/01/2001	IND	65		IS 1893-2002	BIS IS 1893:2014
28	29/02/1960	MAR	20		1982 RPA	2007 RPS
29	31/08/1968	IRN	44		1969-1967 SC 519	2800-05 BHRC:2015
30	1/09/1962	IRN	39		1969-1967	2800-05 BHRC:2015
31	10/07/1949	TJK	35	1935	1951	SNIP 22-07-2007
32	10/08/1931	CHN	25			GB50011-2010(2016)
33	19/09/1985	MEX	57		1987 building code	MOC-2008; NTC 2004
34	29/09/1993	IND	65		1993 - IS4326	BIS IS 1893:2014
35	12/04/1921	CHN	21			GB50011-2010(2016)
36	25/08/1933	CHN	20			GB50011-2010(2016)
37	25/04/2015	NPL	55	NBC105-1994/2004	same	NBC105: 1994/2004
38	15/01/1944	ARG	20		CIRCOC 103-1983	2005 INPRES-CIRSOC 103
39	23/12/1972	NIC	29		1983	RNC-2011
40	16/08/1976	PHL	46	NSCB-1972/1977	NSCB-1982	NSCP-2010
41	22/03/1966	CHN	30		1974 (TJ11)	GB50011-2010(2016)
42	26/05/2006	IDN	59	SNI–02-1726-2002	2009	SNI 1726:2012
43	16/01/1995	JPN	85	1987 - BSLJ	2001	BSL-2016
44	25/06/1976	IDN	32		SNI 1726-1989	SNI 1726:2012
45	23/01/1909	IRN	16			2800-05 BHRC:2015
46	5/08/1949	ECU	15			NEC-SE-DS: 2014
47	16/03/1925	CHN	23			GB50011-2010(2016)
48	1/05/1929	TKM	30	1928	1935	SNT 2.02.01.-98, 2.02.03.-04
49	22/08/1902	CHN	11			GB50011-2010(2016)
50	10/04/1972	IRN	45	1969-1967 SC 519	1988	2800-05 BHRC:2015

51	28/06/1948	JPN	35	1939	1981	BSL-2016
52	10/10/1980	DZA	48		1955 (AS)	RPA-99 (2003)
53	15/08/1950	IND	25		IS I893:1962/1966	BIS IS 1893:2014
54	24/03/1923	CHN	22			GB50011-2010(2016)
55	16/12/1902	UZB	16			KMK 2.01.03-96
56	30/05/1998	AFG	5	Some design		None (1960s)
57	26/11/1943	TUR	34	1940	1944	TEC-2016
58	27/11/1945	PAK	25			NESPAK: 2007
59	3/10/1914	TUR	24			TEC-2016
60	4/02/1998	AFG	5	1970s some design		None (1960s)
61	1/02/1944	TUR	34	1944	1947	TEC-2016
62	17/08/1906	CHL	30		1928	NCh 433 Of.1996 Mod. 2009 + DS 61-2011
63	24/11/1976	TUR	75	1975 (1972 zone)	1981 (Concrete)	TEC-2016
64	31/07/1937	CHN	20			GB50011-2010(2016)
65	28/04/1903	TUR	21			TEC-2016
66	13/02/1902	AZE	16			AzDTN 2.3-1
67	20/04/1935	TWN	23			CPA-2011
68	7/03/1927	JPN	45			BSL-2016
69	28/12/1974	PAK	29			NESPAK: 2007
70	2/03/1933	JPN	45			BSL-2016
71	18/04/1906	USA	25			IBC-2015
72	13/12/1982	YEM	25		YSDC 1991 draft	None (1991)
73	20/12/1942	TUR	33	1940	1944	TEC-2016
74	28/07/1981	IRN	50		1988	2800-05 BHRC:2015
75	13/04/2010	CHN	65	GB 50011-2001.	GB 50011-2010	GB50011-2010(2016)
76	23/11/1980	ITA	65	1975 Law 64	1981 ; 1984	NTC-2008
77	27/04/1931	ARM	30	1928	1935	RABC II-6.02-2006
78	9/08/1912	TUR	24			TEC-2016
79	17/07/1998	PNG	39	1983 Zonation	2013 Checks	None (1980s)
80	12/12/1992	IDN	43	SNI 03-1726-1989	SNI–02-1726-2002	SNI 1726:2012
81	19/08/1966	TUR	57	1968 (1963 zone)	1975 (1972 zone)	TEC-2016
82	6/05/1930	IRN	21			2800-05 BHRC:2015
83	20/09/1999	TWN	73	1997	2005 SDCB	CPA-2011
84	31/03/1931	NIC	7			RNC-2011
85	16/07/1990	PHL	65	1987 - NSCP-1987	1992- NSCP-1992	NSCP-2010
86	6/09/1975	TUR	75	1975 (1972 zone)	1981 (Concrete)	TEC-2016
87	4/11/1952	RUS	40	1951	1957	SP 14.13330.2014
88	12/01/1945	JPN	38	1939	1981	BSL-2016
89	21/05/2003	DZA	65	1999/2003 RPA99	Same	RPA-99 (2003)
90	25/05/1923	IRN	18			2800-05 BHRC:2015
91	6/02/1973	CHN	30		1974 (TJ11)	GB50011-2010(2016)
92	4/02/1975	CHN	35	1974 (TJ11)	1978 (TJ11)	GB50011-2010(2016)
93	19/04/1902	GTM	5			1996/2002 in 17/334 municipalities
94	27/05/1995	RUS	75	1995	2014	SP 14.13330.2014
95	25/01/1999	COL	88	1998 NCDS	2010	NSR-10
96	23/07/1930	ITA	45	1927 - ITALY	1935 - ITALY	NTC-2008
97	30/07/1917	CHN	19			GB50011-2010(2016)
98	4/08/1946	DOM	12			R-001 No. 201-11
99	4/03/1977	ROM	50	1970 - P13-1970	1978 - P100-78	2009 EN 1998-1:2004/AC:2009
100	22/05/1960	CHL	50	1928	1963	NCh 433 Of.1996 Mod. 2009 + DS 61-2011

4. F-N CURVES AND THEIR COMPARISON TO THE TOP 100 EVENTS

The Top-100 events are just one set of events that are possible within the large spectrum of future possible events across countries. For a full analysis of events and the respective risk, an F-N (fatalities per return period) curve is the only possible way of showing the residual risk left in a country after a certain event, and for the possible return period of an event (Jones, 1992). This is because any historical event does not necessarily have a certain return period associated with it. The casualty functions implemented as part of the model are not the main focus of this paper, but simply the methodology with which they can be compared. These were derived in Paper 490, 15ECEE. The reader is referred to Tsang et al. (2018) ECEE, in this conference, for a discussion of fatality risk and F-N curves.

An example is shown for Afghanistan (Figure 4 and Table 4) and then for a number of countries with respect to the Top 100 events. A stochastic event set of 10,000 years was created, and the fatalities calculated via fatality functions using Daniell (2014) and the building stock for Afghanistan in 8 classes. The tail deaths at risk (TDaR) shows the average number of deaths above the PMD (probable maximum deaths) curve. The tail deaths at risk indicate the average number of deaths for the stochastic events with return periods higher than a certain value. The probable maximum deaths represent the number of deaths for a certain return period in the stochastic record. For example, for all events with above 10,000 fatalities in Afghanistan, the average is expected to be in the order of 17,500 deaths and would be a PML160 (160-year return period). This gives an indicator of the tail-end risk at high return period from the stochastic event set.

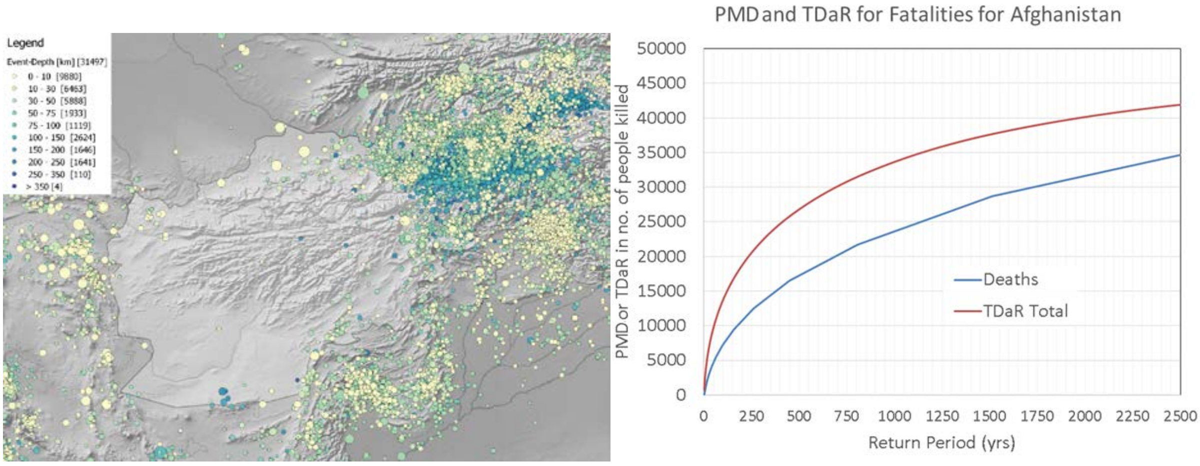


Figure 4. The historical catalogue (left) and the PMD (blue) and TDaR (red) calculated (right)

The two 1998 events in Afghanistan would correspond to around a 35-year event return period when taking the proportion of shaking deaths into account. This would suggest that with the additional historical events since 1900, that the Afghan events seen historically would underestimate the true fatality risk in Afghanistan. The annual average deaths (AAD) of 563 would suggest this as well.

Table 4. Afghanistan Earthquake Deaths (excl. landslide induced deaths) detailing the AAD, PMD for six return periods and the relative loss versus the population. TDaR shows that some of the risk is still present within the stochastic event set, meaning events are more than likely in our lifetime to cause more deaths than experienced in the past 118 years. Occurrence Exceedance Probability (OEP) shows the PMD as a proportion of the population

		Exposed Population:	**27,102,565**
RP	**PMD**	**TDaR**	**OEP as a % of Total Pop**
10	1,275	3,820	0.005%
50	4,690	9,745	0.017%
100	7,285	13,723	0.027%
250	**12,192**	**20,562**	0.045%
500	17,254	26,813	0.064%
1000	23,628	33,661	0.087%
AAD	**563**		**0.0021%**

Moving one step further, analyses between a number of countries have been done in Daniell et al. (2016) which showed the analysis of 33 Eastern European and Central Asian countries. One method that could be used to develop fatality risk taking into account seismic codes and also target levels of building collapse is an F-N curve. These curves measure fatalities against a certain return period of the event as the annual average often does not tell the story of the amount of risk left from potential earthquake scenarios. Similarly, if an annual average were to be presented as the chosen parameter to instill into a code, it may over- or under-estimate the actual acceptability of risk of the local population. This acceptability of risk is very different around the world and would need to be different in each successive code implementation.

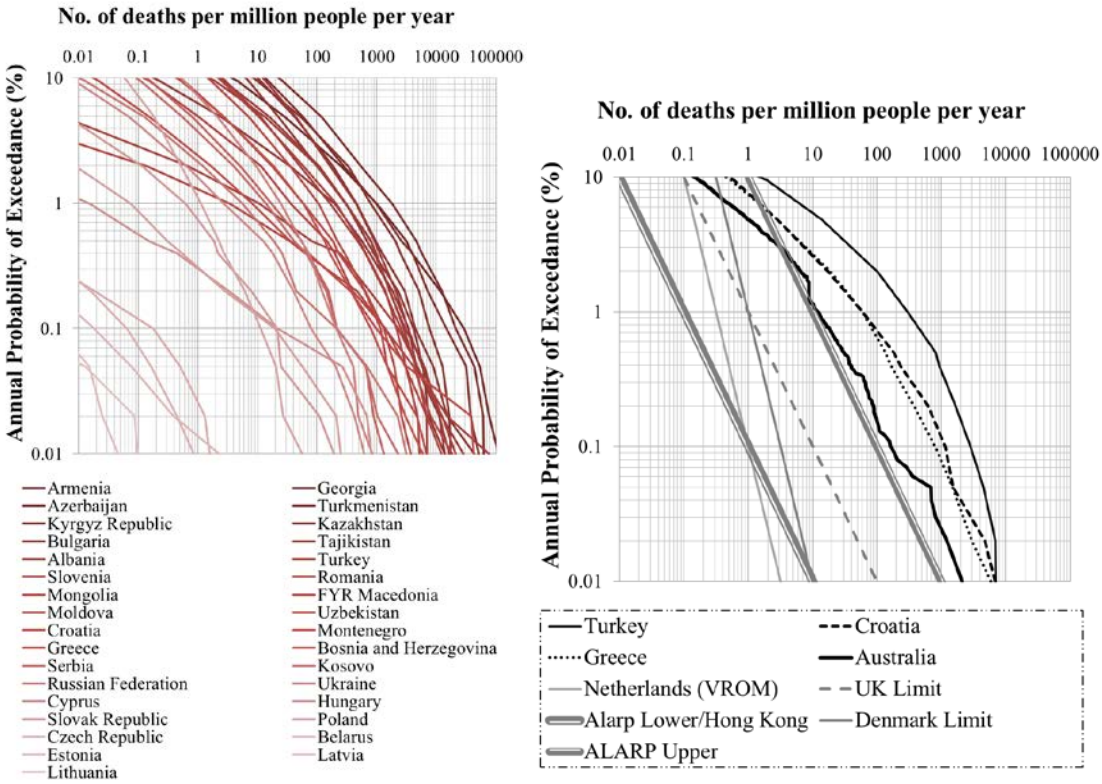


Figure 5. Left: F-N curves for 33 countries in Eastern Europe and Central Asia for earthquakes ordered from highest 0.1% probability of exceedance death toll to lowest (Daniell et al. (2017) via Daniell and Schaefer (2014)). Right: A comparison of 4 stochastic F-N curves vs. limits for life safety.

A historical reanalysis was undertaken in Daniell et al. (2017), where F-N curves were introduced for the largest event in each country since 1500, and stochastic event sets were undertaken. Daniell et al. (2016) looked at the Eastern Europe and Central Asia region, where curves were presented to show the difference in F-N curves for various countries. These are stochastic fatality curves produced from 10000 years of earthquake simulations in Eastern Europe and Central Asia undertaken by Daniell and Schaefer (2014). These curves can be compared to the top 100 events since 1900 for various countries. If we focus on Armenia (the outer most F-N curve), the Spitak earthquake (event 18) caused 25,000 deaths among 3.5 million population (7100 deaths per million people). This would be equivalent to an approximately 1 in 333 year event in the stochastic record (ca. 0.3% annual probability of exceedance). Similarly for the 1931 event in Armenia (event 77), around a 1 in 150 year return period was seen. This suggests that much higher historic fatalities have been seen over the 100-year period than are to be expected in a stochastic 100-year period; or that the modelled fatalities using the updated vulnerability functions and disaster resistant building codes mean that the current stock is better than the older stock leading to less fatalities in the stochastic record.

Turkey is another interesting case, with the 1939 Erzincan event being the major event of the 20th century with a preferred 39,000 deaths. This would be the equivalent of a 0.4% annual rate of exceedance or approximately a 1 in 250 year event at approx. 2250 deaths per million people. It should be noted, that Turkey has since applied many code improvements and this has significantly reduced death tolls e.g the Izmit earthquake of 1999 (around a 270 deaths per million people rate). This improvement was shown in Daniell and Wenzel (2014) and will be shown in a subsequent paper using the actual exposed population per intensity bound for these top 100 events (Daniell and Pomonis, 2018, in prep.).

5. IMPLICATIONS AND CONCLUSIONS

It was the aim of this study to examine the realities of code implementation and to study the historic earthquake events and the potential for fatality risk reduction, learning lessons from the 93% of worldwide earthquake fatalities (2.14 million earthquake fatalities) occurring in the 100 most lethal events since 1900. A first step has been made in rectifying the death tolls from many events combining the Pomonis and CATDAT databases, and looking at the seismic codes in application at the time of the event. This work is important, as countries can learn from such major scenario events and appreciate the potential for reduction of repeat losses. In addition, the need for accountability in terms of death tolls and preparations for governments makes this topic an important one indeed to learn from the uncertainties in death tolls but also the causes of fatalities.

This type of modelling has opened up a number of future studies including:

- Enforcement vs. use of building codes
- Change in vulnerability with respect to AAL and PML in the future (i.e. until 2030)
- Non-residential influence with respect to building codes
- Improvement in life impact i.e. the reduction in number of deaths with respect to school code adherence and importance factors etc.
- Secondary effect modelling in larger events.
- Use with risk-targeted hazard maps (Silva et al., 2014)

Given the large expenditure of time researching the top 100 events and the analysis, examples of life cost saved as a result of code implementation were not explored for various countries in order to see the potential "gap" between code versus non-code implementation, however all isoseismals have been collected and digitized for the 100 events. This analysis will be undertaken in future work using a stochastic risk model and developing a F-N curve of fatalities versus return period and examining also the respective average annual fatalities.

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