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Global earthquake casualties due to secondary effects: a quantitative analysis for improving rapid loss analyses

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Abstract This study presents a quantitative and geospatial description of global losses due to earthquake-induced secondary effects, including landslide, liquefaction, tsunami, and fire for events during the past 40 years. These processes are of great importance to the US Geological Survey's (USGS) Prompt Assessment of Global Earthquakes for Response (PAGER) system, which is currently being developed to deliver rapid earthquake impact and loss assessments following large/significant global earthquakes. An important question is how dominant are losses due to secondary effects (and under what conditions, and in which regions)? Thus, which of these effects should receive higher priority research efforts in order to enhance PAGER's overall assessment of earthquakes losses and alerting for the likelihood of secondary impacts? We find that while 21.5% of fatal earthquakes have deaths due to secondary (non-shaking) causes, only rarely are secondary effects the main cause of fatalities. The recent 2004 Great Sumatra–Andaman Islands earthquake is a notable exception, with extraordinary losses due to tsunami. The potential for secondary hazards varies greatly, and systematically, due to regional geologic and geomorphic conditions. Based on our findings, we have built country-specific disclaimers for PAGER that address potential for each hazard (Earle et al., Proceedings of the 14th World Conference of the Earthquake Engineering, Beijing, China, 2008). We will now focus on ways to model casualties from secondary effects based on their relative importance as well as their general predictability.

Keywords PAGER · Earthquake casualty · Earthquake fatalities · Earthquake hazard

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1 Introduction

A comprehensive catalog of earthquakes of magnitude 5.5 and greater from 1900 to 2008 was compiled to calibrate loss models for the US Geological Survey's (USGS) Prompt Assessment of Global Earthquakes for Response (PAGER) system. This catalog, PAGER-CAT (Allen et al. 2009), comprises several existing databases, including the USGS Preliminary Determination of Epicenters (PDE), the Utsu Deadly Earthquakes Catalog (Utsu), the Emergency Events Database (EM-DAT), and the National Geophysical Data Center's (NGDC) Significant Earthquake and Historical Tsunami Databases (Sipkin et al. 2000, Utsu 2002, Hoyois et al. 2007, Dunbar 2007, respectively). Of these databases, the PDE contains the most detailed information regarding casualties caused by earthquake-induced secondary effects (i.e., landslide, liquefaction, tsunami, and fire). The content of PAGER-CAT allows for a quantitative study of the impact and occurrence of earthquake-induced secondary effects.

It is important to note that the casualty information was compiled from several different databases, and is limited by the quality of information available to the publishers of those data sets. Future versions of PAGER-CAT will include updated casualty information for events for which more reliable sources become available. Fatality statistics contained herein reflect the most recent version of PAGER-CAT available at the time of publishing.

This study focuses on the cause of fatalities during earthquakes and the relative role of earthquake shaking (i.e., from partial or total building collapse) versus secondary causes. Financial impacts from shaking verses other causes are very different, and are rarely reported in detail. Furthermore, previous studies have only looked at a few specific events in detail (e.g., So and Spence 2006; Spence 2007), used proprietary data sets (i.e., Coburn et al. 1989), or focused only on buildings and utilities (e.g., Bird and Bommer 2004; Stafford et al. 2007). In contrast, this study concentrates on the human toll of all fatal earthquakes since September 1968, using an open and publicly available data set.

2 Methodology

Within PAGER-CAT, the PDE is the primary source of information on casualties due to earthquake-induced landslides and tsunami. As of this writing, the PDE contains information on earthquakes from September 1968 to June 2008, thus dictating the years considered in our current analysis. When available, PDE listings include a breakdown of casualty types. For example, the PDE listing of the July 17, 1998 M_{W} 7.0 Aitape earthquake near the north coast of Papua New Guinea is as follows: "At least 2,183 people killed, thousands injured, about 9,500 homeless and about 500 missing as a result of a tsunami generated in the Sissano area. Maximum wave heights estimated at 15 meters. Several villages were completely destroyed and others extensively damaged" (NEIC 1998). This listing yields the following assignments in PAGER-CAT: 0 shaking deaths, 2,183 tsunami deaths, 500 missing, 2,683 total deaths, in addition to information indicating tsunami occurrence and run-up height. In the calculation of total deaths, we assume that those reported missing are casualties.

Sometimes, the PDE does not provide enough information to differentiate the cause of deaths. For instance, the PDE listing of the December 12, 1992 M_{W} 7.7 Flores Region, Indonesia earthquake is as follows: "At least 2,500 people killed or missing in the Flores region, including 1,490 at Maumere and 700 on Babi. More than 500 people were injured and 90,000 were left homeless. Nineteen people killed and 130 houses destroyed on

Kalootoo. Severe damage, with approximately 90 percent of the buildings destroyed at Maumere by the earthquake and tsunami; 50 to 80 percent of the structures on Flores were damaged or destroyed. Damage also occurred on Sumba and Alar. The tsunami on Flores ran inland as much as 300 meters with wave heights of 25 meters. Landslides and ground cracks were reported at several locations on the island" (NEIC 1992). This listing yields the following data: 19 shaking deaths, 2,500 undifferentiated deaths, 2,519 total deaths, and information indicating tsunami and landslide occurrence.

Due to the ambiguity of this PDE entry ("killed or missing"), we would like to divide the undifferentiated deaths into separate shaking, missing, and tsunami death totals. To do this, it is necessary to look for an outside source. In this case, a study by Tsuji et al. (1995) indicates that nearly all the deaths in the Flores region were due to tsunami. This information allows us to change our assignments as follows: 19 shaking deaths, 2,500 tsunami deaths, and 2,519 total deaths.

The presence of undifferentiated fatalities does not mean the numbers given in the PDE are inaccurate. The information contained within the PDE is compiled from news reports and official sources available at the time of publishing. For most events, the PDE does not explicitly state cause of death, and in these cases we assume the casualties to be shaking-related. Reconnaissance work is performed for some events, such as those containing deadly tsunami or landslide, and more accurate numbers occasionally become available. In these cases, we will update PAGER-CAT to reflect this more accurate information.

In addition to shaking, landslide, tsunami, and undifferentiated deaths, the PDE also contains "other" and "missing" deaths. "Other" indicates deaths reported in an earthquake that cannot be associated with one of the aforementioned causes. Examples of these deaths include casualties due to heart attacks or other medical problems, or vehicular accidents attributed to the event. "Missing" can indicate a shaking, landslide, or tsunami-related death, but this fatality assignment may never be disaggregated due to a lack of reconnaissance work after most events.

As discussed, the PDE contains flags for tsunami, landslide, and liquefaction occurrence in addition to casualty information. The Utsu catalog contains tsunami, landslide, and fire flag, while the EM-DAT contains flags for fire, landslide, and tsunami. While there is some duplication of information between the catalogs, the combination of these data sources provides a comprehensive assessment of secondary earthquake occurrence and impacts. Information regarding tsunami occurrence alone is retrieved from the NGDC databases.

As fire and liquefaction/lateral spreading tend to contribute more to structural and financial losses rather than fatalities, information on the specifics of their occurrence and impact are less abundant (Lee et al. 2008). However, their role in earthquake loss and post-disaster response and recovery is significant and should be considered further.

3 Results

3.1 Geospatial analysis

From September 1968 to June 2008, PAGER-CAT lists 18,807 earthquakes, using the following criteria: M 5.5 and greater in active tectonic regions, M 4.5 and greater in stable continent regions, and any earthquake not defined within those criteria where casualties were reported. The epicenter of each event is illustrated in Fig. 1, superimposed on the LandScan 2005 Global Population Database (Bhaduri et al. 2002). Of these 18,807 earthquakes, 749 caused fatalities. The epicenter of each deadly event is illustrated in

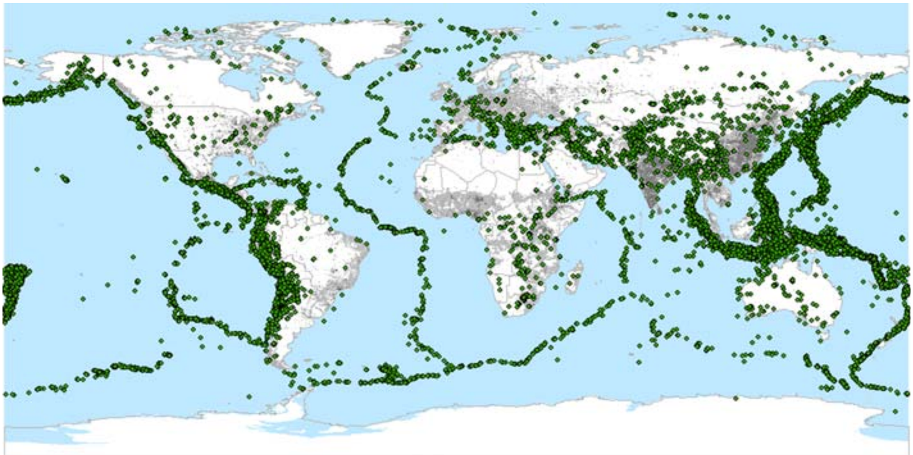

Fig. 1 Epicenters of all earthquakes, September 1968 to June 2008, from PAGER-CAT

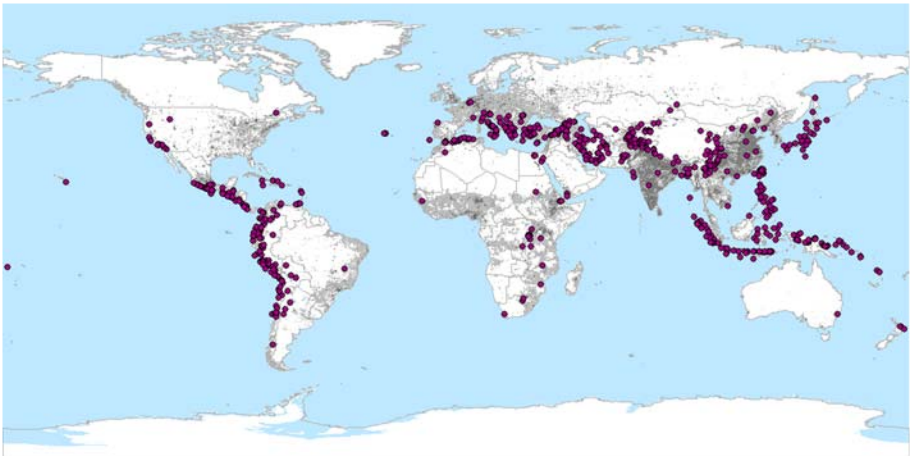

Fig. 2 Epicenters of all deadly earthquakes from September 1968 to June 2008

Fig. 2. Of these 749 events, 161 (21.5%) had deaths due to causes other than earthquake shaking.

As discussed above, PAGER-CAT contains information on earthquake-triggered landslide and tsunami deaths. Epicenters of events where the occurrence of landslides was reported are illustrated in Fig. 3, in addition to events that caused casualties. As seen in the map, fatal earthquake-induced landslides generally occur in areas of large topographic relief, such as the Andes, Alps, and Himalaya. Countries susceptible to landslide-related casualties include: Mexico, Guatemala, El Salvador, Peru, Bolivia, Chile, Uganda, France, Italy, Slovenia, Bosnia and Herzegovina, Greece, Georgia, Kyrgyzstan, Tajikistan, Afghanistan, Pakistan, India, China, Japan, Taiwan, Philippines, Indonesia, Papua New Guinea, and Solomon Islands. Of the 276 events with a landslide flag, 43 were reported to have caused one or more deaths due to landslides.

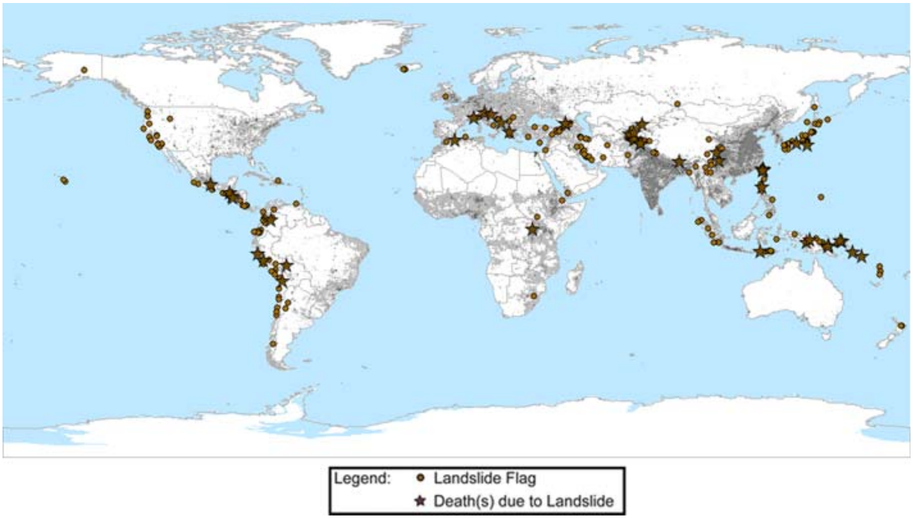

Fig. 3 Epicenters of earthquake-induced landslides from September 1968 to June 2008. A star indicates events with deaths attributed to landslide

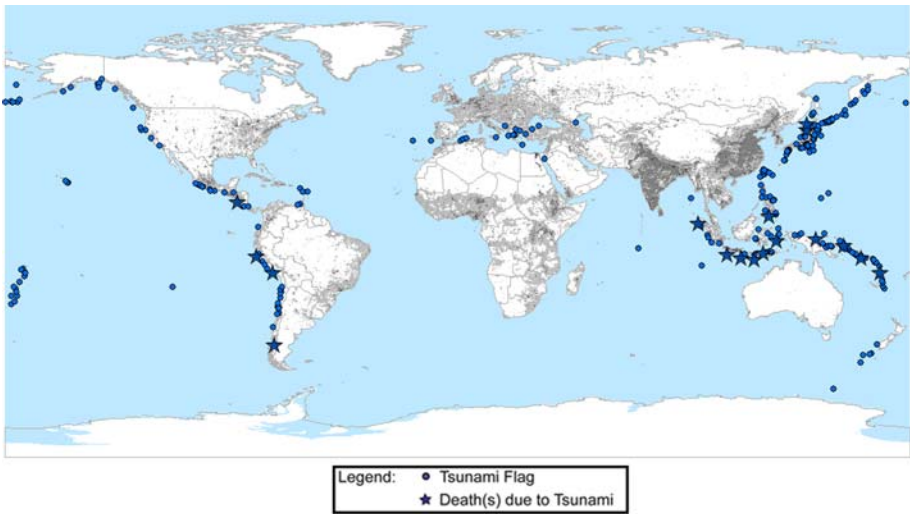

Fig. 4 Epicenters of earthquake-induced tsunami from September 1968 to June 2008. A star indicates events with deaths attributed to tsunami

Epicenters of events where a tsunami was triggered are illustrated in Fig. 4, with events that caused fatalities indicated by a star. From this map, one can infer that earthquake-triggered tsunami generally occur on subduction zone plate boundaries that are capable of generating large mega-thrust events. Earthquakes with fatal events are found in Peru, Chile, Japan, Indonesia, Papua New Guinea, Vanuatu, and Solomon Islands. Of the 298 events with a tsunami flag, 17 had death(s) explicitly reported as due to tsunami.

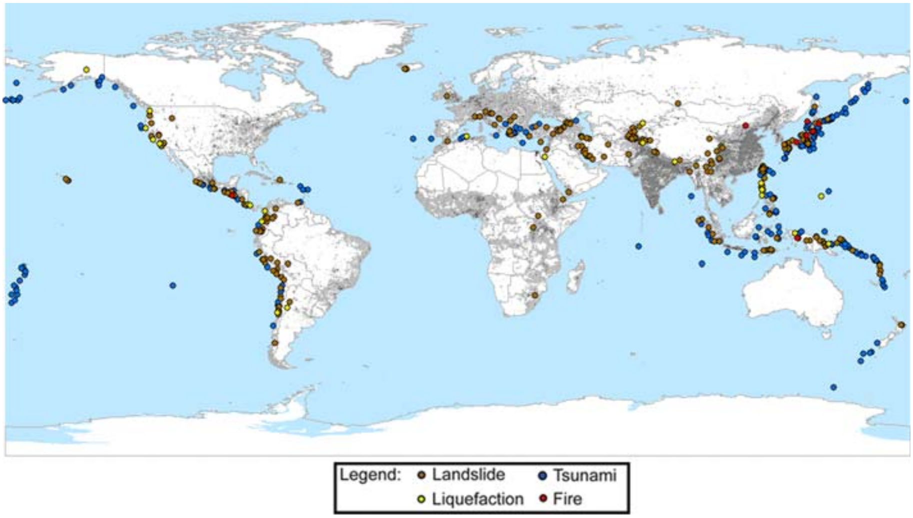

Fig. 5 Epicenters of earthquake-induced landslides (*brown*), liquefaction (*yellow*), tsunami (*blue*), and fire (*red*) from September 1968 to June 2008

Due to the presence of undifferentiated deaths for some events, it is likely that there are additional events with deaths due to landslide and tsunami. However, as discussed earlier, post-earthquake reconnaissance work is not always performed, and the causes of the deaths remain ambiguous. The numbers presented here contain the best information available at the time of publishing.

Earthquake-induced secondary effects occur throughout the world. In the 18,807 earthquakes included in PAGER-CAT since 1968, the following secondary hazards have been recorded: 9 fire (0.05% of all events), 276 landslide (1.47% of all events), 24 liquefaction (0.13% of all events), and 298 tsunami (1.58% of all events). The geospatial distribution of these events is illustrated in Fig. 5. These numbers correlate well with fatality causes, as landslides are both the most abundant and the most deadly (see Sect. 3.2) earthquake-induced secondary effect.

3.2 Quantitative analysis

As the PDE is the primary source of detailed fatality information in PAGER-CAT, the following analysis uses only the PDE. Combining the fatalities for all deadly events from any cause indicated in the PDE (shaking, landslide, tsunami, other, missing, undifferentiated), there were 1,442,342 documented fatalities between September 1968 and June 2008. Of these, as seen in Fig. 6, 1133,878 (77.66%) were due to shaking-related causes, 70,525 (4.83%) were due to landslides, 238,385 (16.33%) were due to tsunami, 430 (0.03%) were due to other causes, 16,423 (1.12%) were listed missing and assumed dead, and 365 (0.02%) were due to undifferentiated causes (Fig. 6). The large number of tsunami fatalities is due to the 2004 Great Sumatra–Andaman Islands earthquake and tsunami. The fatalities from this earthquake dominate the tsunami death totals, at 227,000, and also contribute 1,000 to the shaking total (Cosgrave 2007). Consequently, fatality numbers from the Sumatra–Andaman Islands event are removed from further analyses (Fig. 7). This provides a better representation of the non-shaking fatality distribution for the period

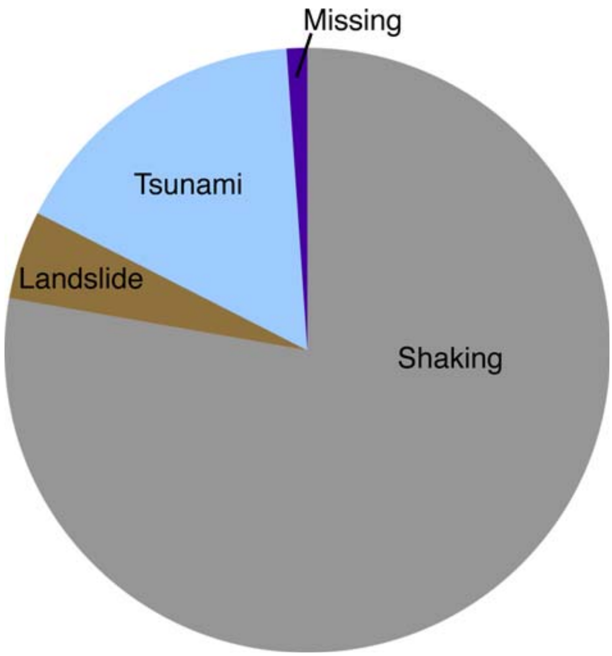

Fig. 6 Fatality causes for all deadly earthquakes between September 1968 and June 2008

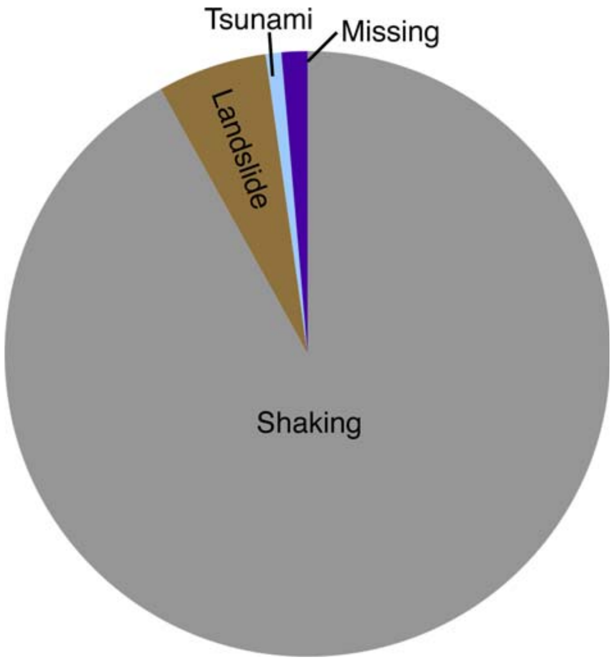

Fig. 7 Fatality causes for all deadly earthquakes between September 1968 and June 2008, with deaths from the 2004 Sumatra event removed

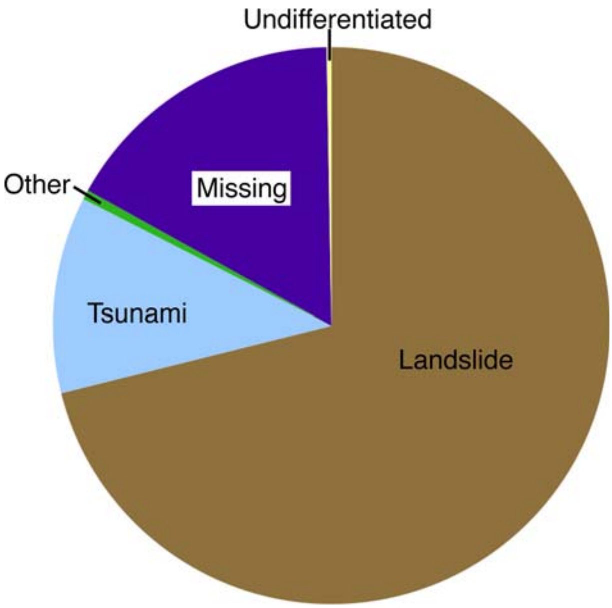

Fig. 8 Non-shaking earthquake fatalities for all deadly earthquakes between September 1968 and June 2008, with deaths from the 2004 Sumatra event removed

covered. Additionally, it is important to note that the death toll of the Sumatra–Andaman Islands event has been updated since the original publication of the PDE. The revised numbers from the 2007 Tsunami Evaluation Coalition Report (Cosgrave 2007) have been used to update PAGER-CAT, and are thus being used in this analysis.

After removal of the 2004 Sumatra data, we observe landslides to be the largest cause of non-shaking deaths in earthquakes. To examine non-shaking deaths in more detail, shaking-attributed fatalities are removed so that only secondary causes are considered (Fig. 8). We observe that landslides are responsible for 71.1% of the non-shaking deaths, followed by tsunami at 11.5%. Since the Great Sumatra–Andaman Islands earthquake was, in many ways, an atypical event, we considered it non-representative and removed it from the determination of the most deadly earthquake-induced secondary effects. However, including the 2004 Sumatra data raises the percentage of earthquake-triggered tsunami deaths to 73.1% (Fig. 9). Landslides subsequently become the second-highest contributor to non-shaking causes of death with 21.6%.

4 Conclusions

A careful study of earthquake casualty statistics over the past 40 years allows us to make several important observations. Earthquake fatalities are dominated by shaking-related causes, while secondary effect-induced fatalities are dominated by landslide deaths. The geospatial clustering of earthquake-induced landslides and corresponding deaths will allow for better casualty estimations for events in these areas.

Naturally, individual events do not conform to these averages, but these earthquake fatality statistics, and their geospatial correlations, provide a basis for probabilistic

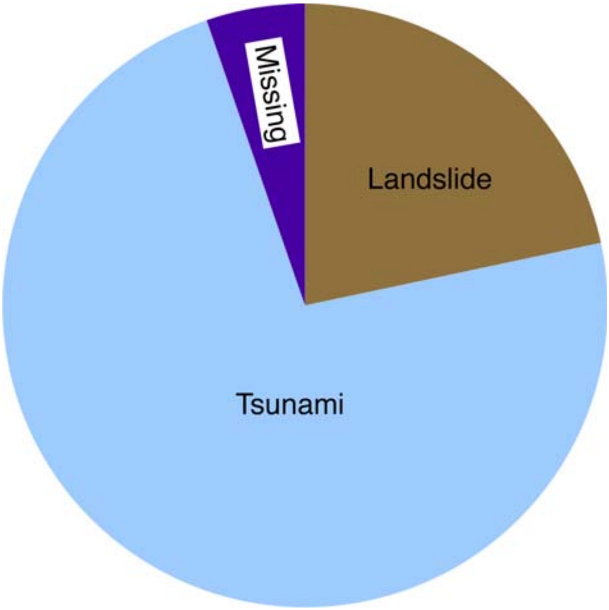

Fig. 9 Non-shaking earthquake fatalities for all deadly earthquakes between September 1968 and June 2008

reporting of the likelihood of fatalities from secondary hazards in specified regions. Furthermore, rapid assessment of the potential occurrence of secondary earthquake effects is of vital importance for post-disaster response and the subsequent recovery of a region. This information will be taken into consideration for prioritizing research and development for the USGS PAGER loss-estimation efforts related to predicting secondary effect-induced fatalities.

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