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# HOW FREQUENTLY DO SMALL-TO-MEDIUM MAGNITUDE EARTHQUAKES CAUSE DAMAGE AND CASUALTIES?

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**Abstract**: *With earthquakes with moment magnitudes in the range **M**4.0-**M**5.5 dominating the seismic hazard and risk in areas where seismicity is predominantly induced by anthropogenic activities, it is of interest to understand what proportion of the earthquakes of this kind that occur worldwide result in damage and/or casualties. To this end, a global catalogue of crustal earthquakes in this magnitude range that have occurred sufficiently close to population or the built environment in the period 2001-2015 has been generated and contrasted against a database of damaging small-to-medium earthquakes compiled in parallel to this work and presented as a separate abstract in this conference. The criteria and methodology used to select the earthquakes that pose a relevant threat—based on the prediction of macroseismic intensity and population exposure—is thoroughly discussed. The resulting statistics are presented in terms of overall number of earthquakes, but also discriminated according to whether they were natural or induced and their cluster status—whether they were main-, fore- or aftershocks. Interpretation of the results is carried out in light of the influence of the availability of information on damage/casualties over these statistics, which becomes apparent in the present work.*

## Introduction

The recognition within the earthquake engineering community of the potential risk posed by induced seismicity has been one of the main causes leading to an increasing interest in small-to-medium magnitude earthquakes in recent years, alongside the continuous development of seismic risk assessment methodologies focused on existent building stocks. As part of a larger effort to understand the risk posed by this kind of earthquakes, this paper presents a study carried out to quantify the proportion of upper-crustal earthquakes with moment magnitude **M** in the range 4.0-5.5 that occur sufficiently close to the built environment that have resulted in damage and/or casualties (Nievas et al., 2019b).

The focus on upper-crustal earthquakes stems from the interest in the application of the results to the context of induced seismicity which, by nature, occurs within depths accessible to human activities, as well as from the fact that deeper earthquakes in this magnitude range are unlikely to represent a major threat. The lower-bound magnitude **M**4.0 was selected on the basis of smaller earthquakes being too unlikely to be damaging (while increasing notably in quantity) as well as from the need of staying above the completeness threshold of the earthquake catalogues used as sources herein. The upper limit of **M**5.5 was adopted based upon the widespread recognition amongst earthquake engineers that seismic events of this magnitude or greater are likely to be damaging (*e.g.*, Bommer and Crowley, 2017). Earthquakes for which damage and/or casualties have been reported have been collected into a database presented as a separate paper in this conference and elsewhere (Nievas et al., 2019c, 2019d).

The study has been carried out at a global scale considering earthquakes that occurred in the 2001-2015 period. The paper describes the methodology followed for the compilation of the catalogue of potentially damaging earthquakes, and for the classification of events into main, fore- and aftershocks as well as into induced and non-induced seismicity. The resulting statistics are presented in terms of these classifications as well as their variation in time, which is heavily influenced by data availability.

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## Methodology

*General Outline*

The methodology followed to carry out this statistical analysis is schematically shown in Figure 1, and consisted broadly of three main stages:

1. compilation of a global earthquake catalogue of upper-crustal earthquakes with moment magnitudes **M**4.0-5.5 (implemented as 3.95≤**M**<5.55) for the period 1st January 2001 – 31st December 2015;
2. identification of potentially-damaging earthquakes within the catalogue, that is, those that occurred sufficiently close to the population/built environment;
3. identification of the actually damaging earthquakes within the set of potentially-damaging ones, and analysis of the outcome.

Details on each of these stages are explained in what follows, while further information can be found in Nievas et al. (2019a, 2019b).

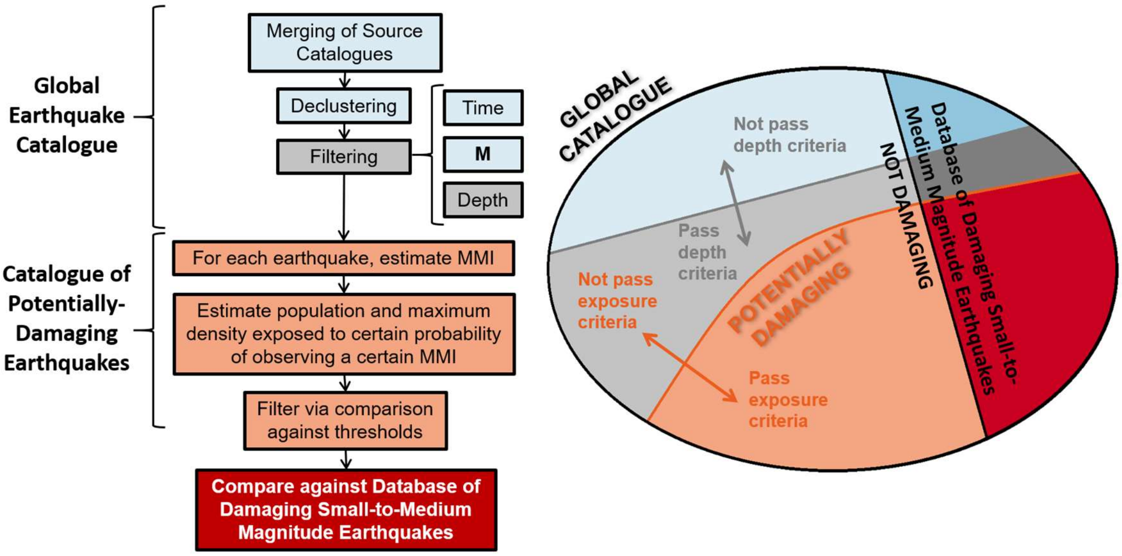

*Figure 1. Outline and schematic representation of the methodology followed and the composition of the catalogue.*

*Compilation of a global earthquake catalogue*

The global earthquake catalogue was compiled taking as a starting point the magnitude-homogeneous catalogue of Weatherill et al. (2016), referred to as WPG16* hereafter (updated version 3c, provided by the authors), complemented with events from the Bulletin of the International Seismological Centre (ISC) that were not already present in the former. A strategy to select one origin and magnitude estimate per event of the ISC Bulletin based on hierarchies of authoring seismological agencies/institutions and areas of influence of national agencies was implemented. Empirical conversion models were used to convert surface-wave magnitude ($M_s$), body-wave magnitude ($m_b$), local magnitude ($M_L$), and duration magnitude ($M_d$) into moment magnitude (**M**), if an estimate in terms of **M** was not directly available from the sources.

While expected (median) **M** values were used for determining inclusion or not of earthquakes in the catalogue, declustering, and determining maximum depths, full probability distributions of **M** were used for the calculation of estimated values of seismic intensity later in the process. Normal distributions were adopted, characterised by the median value of **M** and a standard deviation stemming from the combination of the measurement error of the original magnitude value and the uncertainty of the conversion model used to derive **M**.

Similarly, expected values of hypocentral depth were used for declustering purposes, while full probability distributions were used for the calculation of seismic intensity. The depth errors (*Err*) reported in the ISC Bulletin and the WPG16* catalogue were interpreted as the distance from the median reported depth to either side of the 90%-confidence interval of a normal distribution, from which the associated standard deviation could be calculated as *Err*/1.64. A truncated normal distribution was then used when calculating the probability of the depth complying with a certain limit, but the standard deviation of the unbounded distribution was used for the propagation of uncertainties, as documentation from the ISC suggests *Err* is reported in an unbounded space. Linearly-varying magnitude-dependent maximum depths increasing from 15 km for **M**4.0 to 35 km for **M**5.5 were enforced for the selection of potentially-damaging upper crustal events. An earthquake was considered to comply with this criterion when the probability of the hypocentral depth being equal to or smaller than the limit was equal to or larger than 50%. This was done to account for cases in which the reported standard deviation was so large that the estimate was basically unconstrained (*e.g.*, a 250 km error reported for a depth of 10 km). Earthquakes with fixed depth solutions—identifiable either by means of a flag or because of not being reported with an associated error—were directly compared against the magnitude-dependent maximum depth criterion and assigned the maximum possible value of standard deviation that caused the probability of their depth lying within the limits to be at least of 50%.

The declustering algorithm of Gardner and Knopoff (1974), as implemented in the OpenQuake Hazard Modeller's Toolkit (Pagani et al., 2014), was used to identify foreshocks, main shocks and aftershocks in the catalogue. This classification was used as a proxy to separate cases in which the existence of previous damage or weakening conditions for the structures could be expected (*i.e.*, aftershocks) from those with more likelihood of having affected a previously-undamaged building stock (*i.e.*, foreshocks and main shocks). As discussed in Nievas et al. (2019b), this is a very crude approximation, as strong foreshocks can certainly cause damage that is then aggravated or becomes undistinguishable from that of the main shocks, and the conditions under which progressive damage occurs are too complex to be predicted or determined for a global earthquake catalogue.

The resulting 15-year global catalogue of upper-crustal events with **M**4.0-5.5 comprises 141,524 earthquakes, of which 51,969 (36.7%) were classified as main shocks, 27,192 (19.2%) as foreshocks, and 62,363 (44.1%) as aftershocks.

### *Global catalogue of potentially damaging events*

The next step of the process consisted on the identification of the potentially-damaging earthquakes within the global catalogue. Potentially-damaging was herein understood as occurring sufficiently close to the built environment to represent a threat, the most obvious counterparts being earthquakes occurring in the middle of oceans or deserts. The criterion used to determine whether an earthquake happened sufficiently close or not was based on using population counts and densities from Gridded Population of the World GPW v4.0 (CIESIN, 2016) and intensity prediction equations (IPE) to calculate the total number and maximum density of people exposed to estimated levels of seismic intensity, as schematically depicted in Figure 2.

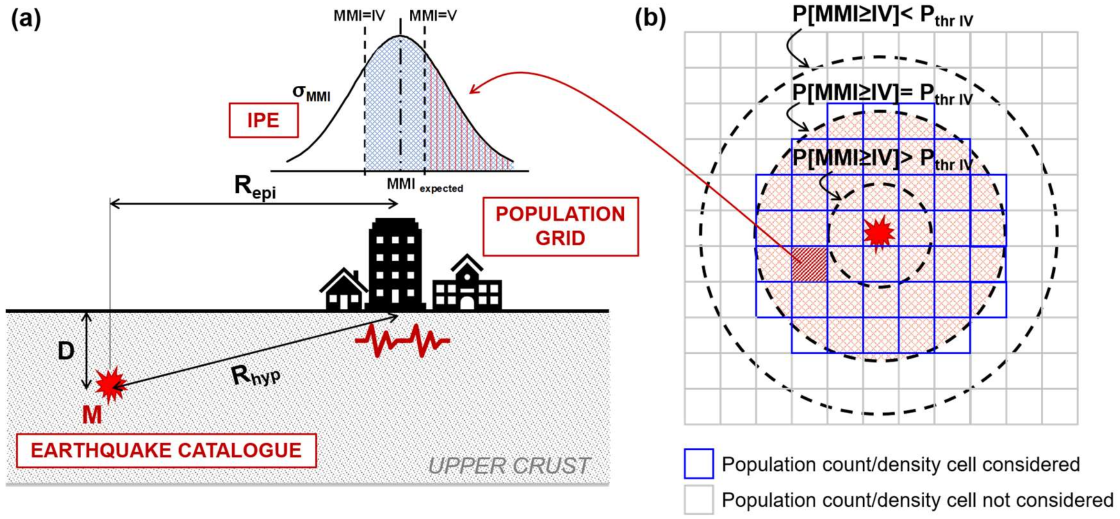

*Figure 2. Schematic representation of the criterion used to determine whether an earthquake occurred sufficiently close to the built environment so as to pose a threat or not: (a) side view and (b) plan view. The plan view exemplifies the criterion using the probability of observing MMI values of IV and its associated probability threshold ($P_{thr\ IV}$).*

The IPEs of Atkinson and Wald (2007) with their two sets of coefficients—for stable continental and active crustal regions—and the craton index (CI) of Chen et al. (2018) were used to calculate complete distributions of Modified Mercalli Intensities (MMI) accounting for the variability of attenuation properties of different tectonic environments and the uncertainty in **M**, hypocentral depth and the empirical IPE, as described in Nievas et al. (2019b). The points selected to carry out these calculations were the geometrical centres of the GPW grid cells. For each cell, the probability of attaining MMI values of IV and V were calculated, as shown in Figure 2(a). Each cell was then considered in the final count if the probabilities exceeded the magnitude-dependent thresholds pre-defined as per Figure 3 or discarded otherwise. The earthquake was considered to pose a threat if the summation of the population count from all considered cells was equal to or larger than 2,500 or if the density in any of those cells exceeded 300 people/km$^2$. The catalogue of potentially damaging earthquakes was then composed of all the earthquakes that satisfied this criterion, referred to as the “exposure criterion” hereafter for simplicity.

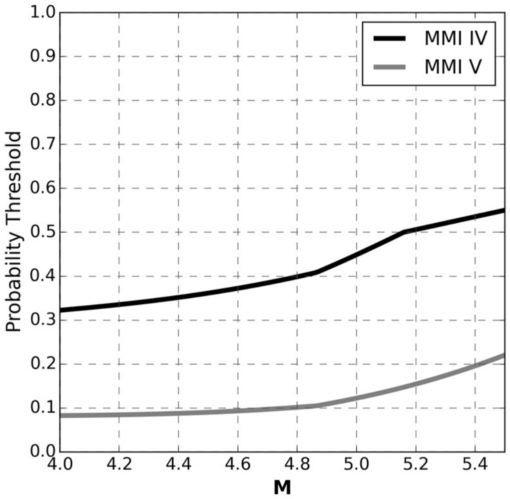

*Figure 3. Magnitude-dependent probability thresholds for MMI≥IV (black) and MMI≥V (grey).*

The probability thresholds shown in Figure 3 were defined so that an earthquake occurring at the maximum depth considered for its magnitude was able to cause these probabilities at least in the cell that contained its epicentre, as imposing larger thresholds would result in an effective reduction of the maximum depths. In other words, this approach considers that an earthquake whose depth is the maximum considered for its magnitude is potentially damaging if the population count or density of the GPW grid cell where the epicentre falls comply with the 2,500 people or 300 people/km$^2$ thresholds. As a consequence, the choice of the specific levels of MMI to consider is of minor importance, as the key lies in the probability thresholds being defined as those right at the epicentre of an earthquake with maximum hypocentral depths. The interested reader can refer to Nievas et al. (2019a, 2019b) for details on the calculation of the values shown in Figure 3 as well as on the selection of the 2,500 people and/or 300 people/km$^2$ thresholds.

Of the 141,524 events encompassed in the global catalogue of upper-crustal events with **M**4.0-5.5, 39,127 (27.6%) pass this exposure criterion and make up the catalogue of potentially damaging events. These are depicted in salmon and red in Figure 4, which also shows in grey those earthquakes that do not comply with the exposure criterion.

### *Flagging of induced earthquakes*

Three sources were used to classify the potentially damaging events into induced and non-induced seismicity, with the purpose of allowing the results of this study to be disaggregated accordingly; an overview of approaches to such discrimination is given by Verdon et al. (2019). These were: the WPG16* catalogue, the ISC Bulletin and the Human-Induced Earthquake Database (HiQuake) (Foulger et al., 2018). Processing of the first for this purpose was simple, as the WPG16* catalogue contains a field flagging induced events. The toolkit published alongside the paper of Weatherill et al. (2016) was used to process comments from the ISC Bulletin identified as containing the keywords “geothermal", "reservoir", "mining", “anthropogenic" and “rockburst”. As the ISC Bulletin is also the source for the flagging contained in the WPG16* catalogue, the classification from the two matched in almost all cases, except for very few in which the events had been updated in the ISC Bulletin after the compilation of the WPG16* catalogue. For this reason, the two are merged as one methodology in what follows.

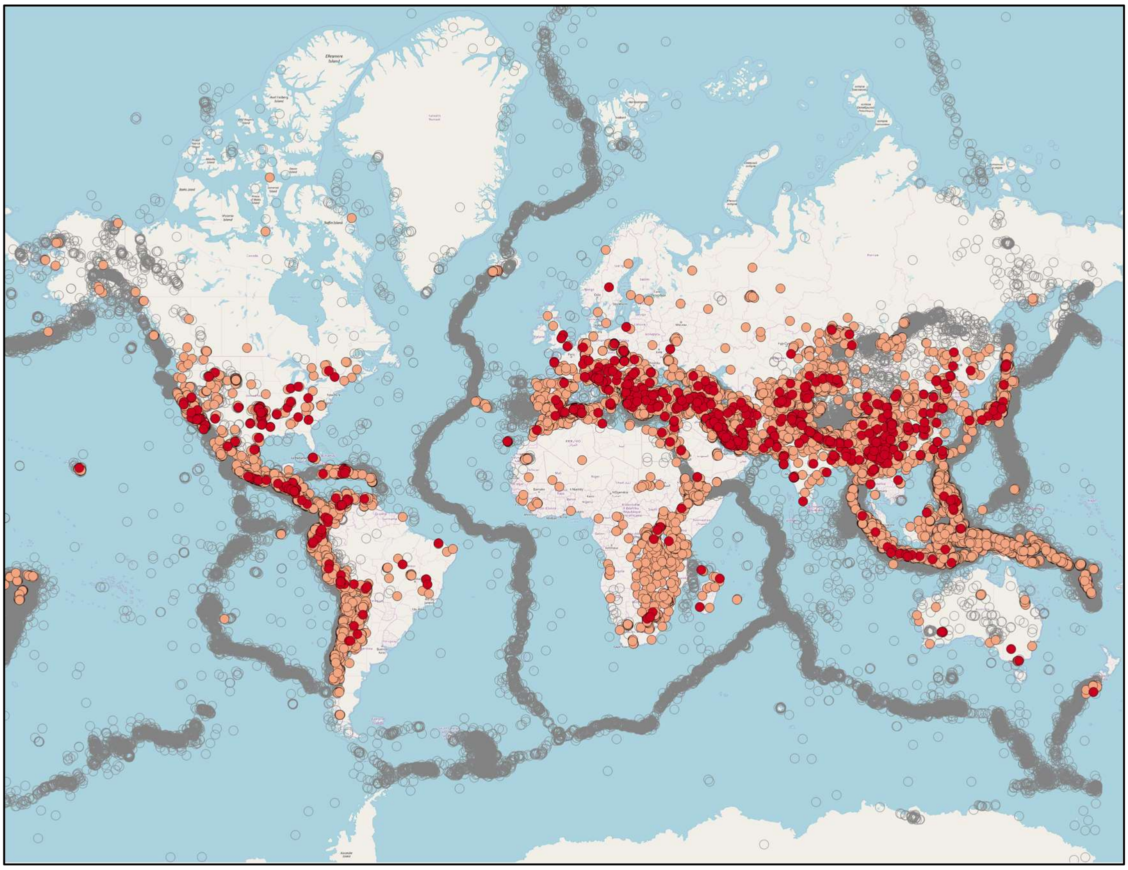

*Figure 4. Global earthquake catalogue (light grey; 141,524 events), catalogue of potentially damaging earthquakes (light salmon; 39,127 events) and damaging earthquakes within the latter (red; 740 earthquakes). Background world map from OpenStreetMap.*

The last source used was the HiQuake database (Foulger et al., 2018), which is a compendium of cases of induced seismicity reported in terms of the projects and precursory activities that allegedly generated them. As such, a scheme was developed to transform each entry of HiQuake into spatial and temporal windows such that earthquakes with epicentres and origin times falling within them would be classified as induced. As the area of the observed seismic activity and its starting and finishing dates were not always readily available from HiQuake, assumptions had to be made to fill in the missing information. Quality indicators were thus defined to keep track of the level of reliability of the classification. For example, the start and end dates were deemed as being of maximum quality (‘A’) if the dates of start/end of seismicity/monitoring were reported in HiQuake, intermediate quality (‘B’) if they could be inferred by the start/end date of the project in conjunction with information regarding the temporal extent of seismicity associated to particular anthropogenic activities, and low quality (‘C’) if no start or end dates could be assigned (the influence of that causative activity was then assumed to have been always present). A radius and an offset were used to define a circle of influence centred in the coordinates reported in HiQuake. Quality flags of ‘A’ (high) or ‘C’ (low) were assigned to these depending on whether they were calculated from information available in HiQuake or if pre-defined values depending on the kind of causative activity were adopted. Details on the assumptions and methodology used can be found in Nievas et al. (2019a).

Table 1 shows the classification into induced and not induced resulting from considering the ISC Bulletin and the WPG16* catalogue, and that based on the interpretation of data from HiQuake. As can be observed, the former leads to a smaller percentage of induced events than the latter (0.9% vs. 6.7%). This is not surprising, particularly when observing that a large proportion of the earthquakes classified as induced based on HiQuake but non-induced based on the ISC Bulletin and the WPG16* catalogue correspond to low-quality spatial and temporal windows, as shown in Figure 5. These pie plots depict the best quality indicator for a particular earthquake, which means that if the earthquake is classified as induced due to two or more different entries of HiQuake, one with quality A and the other with quality B, for example, quality A is shown. As can be observed, 23.3% of the earthquakes were classified as induced with the activity not having had a specific start date, and 55.4% were in a similar situation with respect to the end date. It is clear from Figure 5 as well that most areas of influence were defined by adopting generic values for different kinds of causative activities (*e.g.*, geothermal, mining, oil and gas, etc.). What is most interesting, however, is that when repeating the analysis for the 203 cases flagged as induced with the two methodologies, the proportions of bad-quality indicators is much larger, with only one earthquake featuring A quality in any indicator (the start date in this case), around 90% featuring B quality for the start date, all earthquakes featuring C quality in indicators for radii and offsets, and most activities not having a defined finishing time of influence. This suggests that agreement between the two methodologies to flag induced earthquakes is not a synonym of data quality within HiQuake, as may have been expected.

| | | **Based on HiQuake** | | **Total** |
|---|---|---|---|---|
| | | **Induced** | **Not Induced** | |
| **Based on ISC Bulletin and WPG16*** | **Induced** | 203 | 138 | 341 |
| | **Not Induced** | 2,436 | 36,350 | 38,786 |
| **Total** | | 2,639 | 36,488 | 39,127 |

*Table 1. Classification of the catalogue of potentially damaging events into induced and not-induced according to different methodologies.*

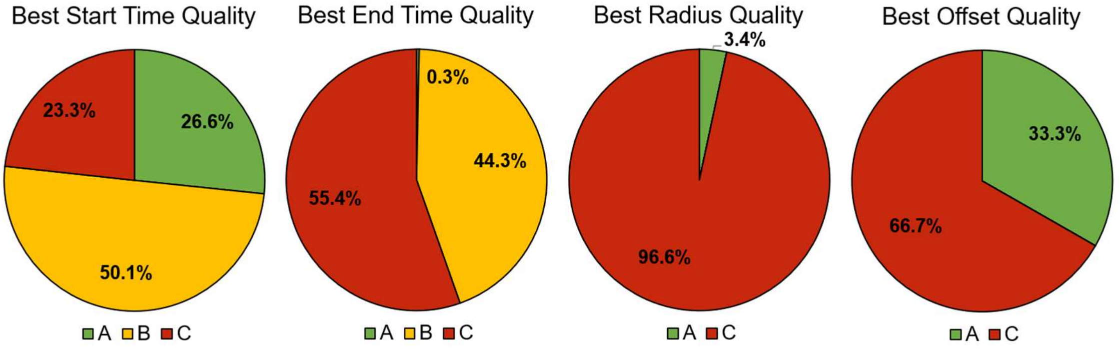

*Figure 5. Best quality indicator for a particular earthquake, ranging from highest (A) to lowest (C) quality, for the 2,436 cases classified as induced with the methodology based on HiQuake but as non-induced with the methodology based on the ISC Bulletin and the WPG16* catalogue.*

It is noted that both methodologies suffer from limitations, as classification according to the ISC Bulletin relies on the flagging carried out by the contributing agencies as well as on the use of particular keywords, while classification according to data from HiQuake relies on the quality of the data used to compile it and the assumptions that were needed so as to convert it into spatial and temporal windows that could be used for this purpose. Consequently, none of the two can be deemed to be providing the final answer but only to be serving as an indication on broad numbers.

## Proportion of damaging earthquakes

Having defined the catalogue of potentially damaging earthquakes, the final step of this study consisted in identifying the earthquakes within the catalogue that actually caused damage. This was done by means of comparing the former against the Database of Damaging Small-to-Medium Magnitude Earthquakes, a database of earthquakes with moment magnitude **M**4.0-5.5 reported to have caused damage and/or casualties which has been compiled and presented separately (Nievas et al., 2019c, 2019d). The database encompasses 996 earthquakes for the time period of interest, of which 740 can be found within the 39,127 events identified as potentially damaging. Those 256 that could not be found are:

- 30 cases that are part of the global catalogue composed of 141,520 earthquakes but do not comply with the exposure criterion;

- 213 earthquakes that were part of the initial unfiltered catalogue but do not pass the maximum depth criteria;
- six events that lie outside the defined magnitude range, either due to floating point precision or the selection of different magnitude estimates from different seismological agencies;
- seven cases that are not found at all, either because they are not present in the ISC Bulletin, they only have magnitude estimates in scales not considered herein, or they are potentially misclassified as explosions in the initial stages of compilation and, thus, discarded.

While details on the 30 and 213 earthquakes that do not comply with the exposure and depth criteria, respectively, can be found in Nievas et al. (2019a, 2019b), what is most important to note here is that modifications in the criteria that would lead to the inclusion of these events in the catalogue of potentially damaging earthquakes would likely lead as well to smaller proportions of damaging earthquakes as more non-damaging events get drawn into the set as well. This conclusion was reached by observing an almost linear decrease of the percentage of damaging earthquakes with increasing numbers of events in the catalogue resulting from the implementation of less restrictive population thresholds (*i.e.*, values smaller than 2,500 people and/or 300 people/km$^2$) (Nievas et al., 2019b).

Focusing on the 39,127 potentially damaging earthquakes and the 740 actually damaging cases within them (marked in red in Figure 4), Table 2 summarises the results obtained. As can be observed, 1.9% of all the potentially damaging earthquakes reportedly caused damage and/or casualties, with this percentage rising to 3.3% when considering only main shocks and going down somewhere in between to 2.7% when considering main- and foreshocks together. The proportion decreases significantly to a 0.9% for aftershocks, a fact that might be due to a combination of three reasons: (i) the difficulties associated with recording damage caused by a particular aftershock as consequences are many times reported for the whole sequence, (ii) the likelihood that earthquakes in the range **M**4.0-5.5 that are classified as aftershocks occur in areas of high seismicity, where buildings might be better designed and people are probably used to shaking, all together leading to minor damage caused by aftershocks getting less reported, (iii) the tendency of aftershocks to have lower stress drops than main shocks and consequently result in lower ground motions, when both main shock and aftershock rupture the same part of the fault (*e.g.*, Abrahamson et al., 2014; Wooddell and Abrahamson, 2014). What is interesting to note is that including the aftershocks in the statistics does not lead to an increase in the resulting proportions of damaging earthquakes as could have been expected from the concept of incremental damage (*e.g.*, a building collapsing during a small-magnitude aftershock because it had been pre-weakened by a stronger main shock), but the opposite.

| **Kind of Shock** | **ALL** | | |
|---|---|---|---|
| | **Total** | **Dam.** | **%** |
| **All Shocks** | 39,127 | 740 | 1.9 |
| **Main and Fore-** | 21,475 | 584 | 2.7 |
| **Main Shocks** | 15,123 | 498 | 3.3 |
| **Foreshocks** | 6,352 | 86 | 1.4 |
| **Aftershocks** | 17,652 | 156 | 0.9 |

*Table 2. Proportion of damaging events within the catalogue of potentially damaging earthquakes, classified in terms of kind of shock.*

As a consequence of the Gutenberg-Richter relationship (Gutenberg and Richter, 1944) and the larger destructive power of larger-magnitude events, the proportion of damaging earthquakes increases with magnitude, as depicted in the plot on the right of Figure 6. As shown in the plot on the left, the number of potentially damaging earthquakes generally increases in time as well, and the proportion of damaging events sees a significant jump from the year 2012 to 2013. The same trend can be observed when main shocks, aftershocks and foreshocks are analysed separately. Both phenomena are due to the influence of data availability. In the first case, the increase is likely connected to improvements in the detectability of small-magnitude earthquakes and of the worldwide coverage of the network, as well as an increase in the number of seismological agencies that contribute to the ISC Bulletin. In the second case, the number of earthquakes present in the Database of Damaging Small-to-Medium Magnitude Earthquakes increases significantly in the year 2013, as shown in Figure 7, due to the incorporation of data from the Earthquake Impact Database (EID), which is compiled online in almost real time. Table 3 summarises the variation in the proportion of damaging earthquakes for different time periods and suggests that it is thus possible that 4.3% be a more realistic percentage of damaging earthquakes than 1.9%, when all shocks are considered, and 6.2% be more realistic than 2.7% when considering only main shocks and foreshocks. As it is still possible that earthquakes that caused damage and/or casualties be missing from the EID, these proportions could be even larger. If adding the 256 earthquakes from the Database of Damaging Small-to-Medium Magnitude Earthquakes that are not included within the 39,127 potentially damaging events without adding any other non-damaging events (*i.e.*, the unlikely worst case-scenario in which changing the criteria for defining the set of potentially damaging earthquakes only leads to damaging earthquakes being drawn towards the set), the proportions of damaging earthquakes rise up to 2.5% for the whole time period and 1.3% and 5.8% for 2001-2012 and 2013-2015, respectively. While large in terms of relative increase, it is interesting to note that even such an extreme assumption does not cause the proportions of damaging events to skyrocket.

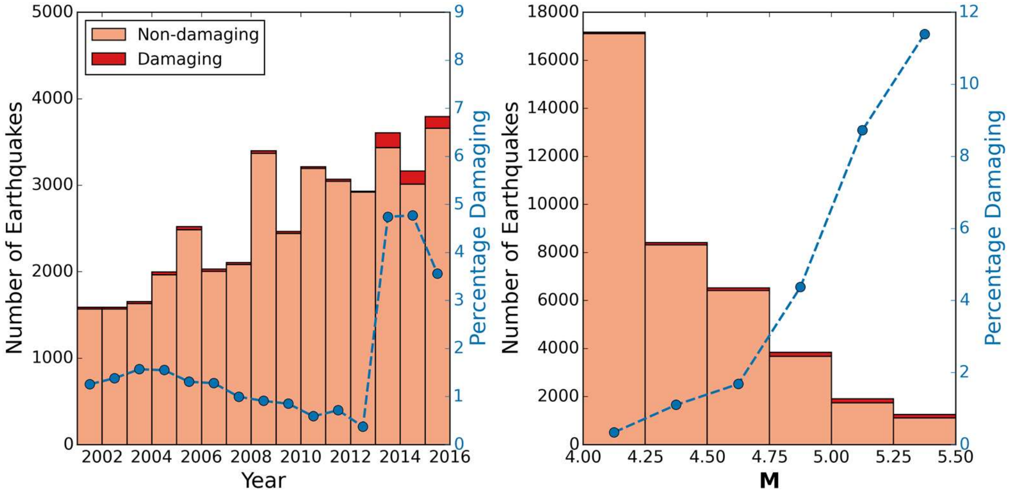

*Figure 6. Distribution of potentially damaging earthquakes in time (left) and by moment magnitude (right). Damaging and non-damaging events indicated in red and salmon, respectively. Blue dots indicate the percentage of damaging events per bin.*

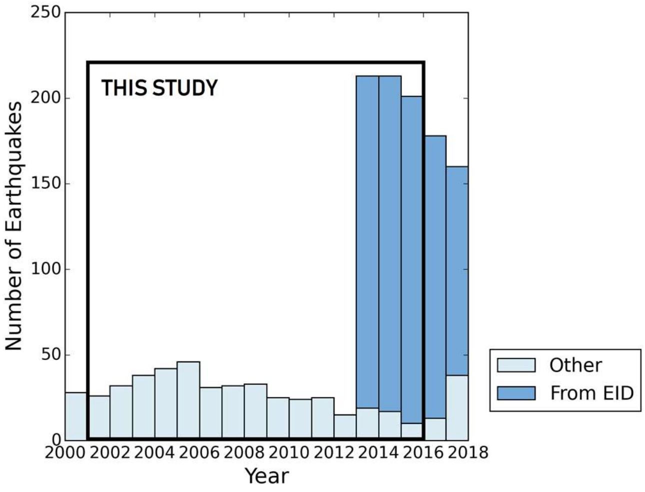

*Figure 7. Distribution in time of the earthquakes that make up the Database of Damaging Small-to-Medium Magnitude Earthquakes (**M**4.0-5.5, Nievas et al. 2019d) for the years 2000-2017. The rectangle encloses the period considered for the present study.*

| **Kind of Shock** | **2001-2015** | **2001-2012** | **2013-2015** | **2013** | **2014** | **2015** |
|---|---|---|---|---|---|---|
| **All Shocks** | 1.9 | 1.0 | 4.3 | 4.7 | 4.8 | 3.6 |
| **Main and Foreshocks** | 2.7 | 1.4 | 6.2 | 7.7 | 6.3 | 4.9 |

*Table 3. Proportion of damaging earthquakes for different time periods and years.*

It is of interest as well to investigate the variation of the percentages of damaging earthquakes separating induced from natural events, as presented in Table 4. Given that the overall proportion of induced earthquakes is relatively small, the percentage of damaging natural earthquakes is similar to that of the whole set, but a notable increase can be observed when looking only at the induced events. In this case, the total percentage of damaging earthquakes rises from 1.9% to 2.3-2.9%, depending on the methodology used to flag induced cases. This increase is possibly due to damage linked to small-to-medium magnitude induced earthquakes being more likely to be reported than that of their natural counterparts, mostly because the former is perceived as imposed and avoidable. It is interesting to note that, while the overall proportion of induced earthquakes changes significantly from 0.9% to 7.1% when using either of the three sources (ISC Bulletin, WPG16*, HiQuake) instead of just two (ISC Bulletin, WPG16*), the proportion of damaging induced earthquakes increases at a much lower rate, from 2.3% to 2.9%.

| **Classification Strategy** | **INDUCED** | | | **NON-INDUCED** | | |
|---|---|---|---|---|---|---|
| | **Total** | **Dam.** | **%** | **Total** | **Dam.** | **%** |
| **ISC Bulletin + WPG16*** | 341 | 8 | 2.3 | 38,786 | 732 | 1.9 |
| **ISC Bulletin + WPG16* + HiQuake (1)** | 2,777 | 80 | 2.9 | 36,350 | 660 | 1.8 |

(1) An earthquake is classified as induced if flagged as such in either of the three sources.

*Table 4. Proportion of damaging events within the catalogue of potentially damaging earthquakes, classified in terms of kind of shock and induced/non-induced as per flagging in the ISC Bulletin + WPG16* and based on the HiQuake database (Foulger et al., 2018).*

## Conclusions

This paper has presented a statistical analysis carried out to quantify how frequently upper-crustal earthquakes with magnitudes **M**4.0-5.5 that occur sufficiently close to the built environment result in damage and/or casualties. Results show that an average of 1.9% of the potentially damaging earthquakes have been identified as damaging or causing casualties in the period 2001-2015, though the variation of this number in time is significant. With the number of damaging earthquakes presenting a clear jump between 2012 and 2013 due to the incorporation of data from the Earthquake Impact Database (EID) from 2013 onward, the proportion of damaging earthquakes is around 1.0% for 2001-2012 and 4.3% for 2013-2015.

Incorporation into the set of potentially damaging earthquakes of damaging events reported in the Database of Damaging Small-to-Medium Magnitude Earthquakes but not found in the aforementioned set under the extreme assumption that a loosening of the criteria leads to the incorporation of only damaging earthquakes but no no-damaging ones leads to an increase of the proportion of damaging earthquakes from 1.9% to 2.5% for the complete 15-year period, and from 1.0% to 1.3% for 2001-2012 and from 4.3% to 5.8% for 2013-2015. However, the testing of different population thresholds suggests that loosening of the criteria leads to decreasing proportions of damaging earthquakes instead, as in reality more non-damaging than damaging events get pulled into the catalogue.

Results show as well that the percentage of damaging earthquakes is larger for induced (2.3-2.9%) than for non-induced events (1.8-1.9%), and for main shocks (3.3%) or main shocks combined with foreshocks (2.7%) than for aftershocks (0.9%) or all kinds of shocks together (1.9%). The former is believed to be heavily influenced by a stronger tendency to report damage from earthquakes perceived as imposed than from tectonic ones, while the latter is likely related to the difficulties associated with assigning specific consequences to any particular aftershock in a sequence, the likelihood of many of these aftershocks corresponding to large damaging main shocks occurring in areas of high seismicity in which slight damage might pass unnoticed, and the tendency of aftershocks to cause lower ground motions than their corresponding main shocks when both main shock and aftershock rupture the same part of the fault.

It is noted that there is not a correct or incorrect way of defining the catalogue of potentially damaging **M**4.0-5.5 upper-crustal earthquakes and, consequently, results shown herein reflect the decisions made during the compilation process. The challenges addressed along this work and the large influence of data accessibility on the number of identified damaging events suggest that the proportions of damaging earthquakes determined herein may be lower bounds. Further refinements of the study could look into statistics within smaller sub-ranges of magnitude, consideration of all depth and magnitude estimates for each earthquake, and examining the specific characteristics of the most outstanding examples of damaging small-magnitude events.

## Acknowledgements

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