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# GLOBAL ASSESSMENT OF HUMAN LOSSES DUE TO EARTHQUAKES

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## ABSTRACT

Current studies have demonstrated a sharp increase in human losses due to earthquakes. These alarming levels of casualties suggest the need for large-scale investment in seismic risk mitigation, which, in turn, requires an adequate understanding of the extent of the losses, and location of the most affected regions. Recent developments in global and uniform datasets such as instrumental and historical earthquake catalogues, population spatial distribution and country-based vulnerability functions, have opened an unprecedented possibility for a reliable assessment of earthquake consequences at a global scale. In this study, a uniform probabilistic seismic hazard assessment (PSHA) model was employed to derive a set of global seismic hazard curves, using the open-source software OpenQuake for seismic hazard and risk analysis. These results were combined with a collection of empirical fatality vulnerability functions and a population dataset to calculate average annual human losses at the country level. The results from this study highlight the regions/countries in the world with a higher seismic risk, and thus where risk reduction measures should be prioritized.

## INTRODUCTION

Due to the exponential increase in world population and establishment of large settlements in hazard-prone areas, losses in natural disasters have doubled in the last two decades (World Bank, 2006). According to Cummins and Mahul (2009), when expressing the economic losses as a fraction of a country's gross domestic product, it is the low- and middle-income countries the most affected by natural disasters, as opposed to high-income countries where risk reduction campaigns and strategic urban planning are commonly endorsed, thus highlighting the importance of establishing disaster mitigation policies.

Understanding the magnitude of human and economic losses worldwide is fundamental for large-scale disaster risk reduction investment. In the last 20 years, about 13.5 billion $US have been financed by various institutions (e.g. World Bank, European Commission) and governments (e.g. Japan, USA, Australia) in the implementation of disaster mitigation in regions frequently struck by

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natural disasters (Kellett and Caravani, 2013). The support provided by the international community to each region is not proportional to the population at risk, but rather focused on the areas where catastrophic events have occurred recently (e.g. China, India, Indonesia). This leads to an investment scheme in which an important fraction of the funds are allocated to post-disaster emergency relief and recovery, rather than risk reduction measures, which often have a lower economic cost, and allow a direct reduction of human losses. A successful example of a risk mitigation action is the case of the electrical network in New Zealand, in which an investment of 6 million $US in seismic strengthening and retrofitting of the distribution network, saved an estimated amount of 36 million $US from the Christchurch earthquake in 2011 (Global Assessment Report, UNISDR (2013)).

In particular, earthquakes have caused more than 700,000 fatalities in the last decade, and just in the year of 2011 economic losses totalling 380 billion $US were reported, making it the costliest year ever recorded(MunichRe, GeoRisks Research NatCatSERVICE 2011-http://www.munichre.com/en/media-relations/publications/press-releases/2012/2012-01-04-press-release/index.html). The estimation of losses due to earthquakes involves compiling databases of earthquake activity, soil conditions, ground motion attenuation models, information regarding the exposed inventory, and vulnerability models relating loss fraction with ground shaking (Crowley et al., 2006). Though these components might be available for some parts of the world, their compilation at a global scale is impractical, mostly due to lack of data, tools and knowledge. Furthermore, the availability of data and models does not ensure their validity for loss estimation, unless calibration against historical earthquakes is performed (Jaiswal and Wald, 2013), which is only possible for a few parts of the world.

These impediments propelled the development of simplified approaches to globally assess current potential human and economic losses, as well as to predict trends for future losses, which is useful information to plan long-term risk reduction measures. Bilham (2004, 2009) investigated the cumulative distribution of fatalities between 1500 and 1999, and concluded that a power law fits these data adequately, if events with large number of fatalities are disregarded in the regression analysis. However, these two studies in which only earthquakes with less than 5,000 and 30,000 deaths were considered, led to trends that generally underestimated the observed fatalities in the decade of 2000-2009, thus reducing their predictive value. More recently, Holzer and Savage (2013) carried out a comprehensive study to understand the relation between global fatalities and population, and how these links can be utilized to forecast human losses due to earthquakes. Their study concluded that global earthquake fatalities could be reasonably predicted by considering two sources: a) steady background fatalities which seem to be independent of population growth; and b) fatalities from large catastrophic earthquakes (above 100,000 deaths) which seem to obey a nonstationary Poisson process with a rate proportional to world population. Regardless of the different processes and conclusions, both studies relied on statistical analysis at a global scale of earthquake fatality catalogues, and thus do not fulfil the need for country or regional-based loss estimations.

In the present study, country-based human losses are estimated using a number of uniform global datasets, which provide more detailed information for earthquake loss estimation. These include the spatial distribution of population, earth crustal strain rate, instrumental and historical earthquake catalogues, simplified shear wave velocity estimations, and country-based empirical fatality models. Some of these datasets and models have been created or further developed as part of the Global Earthquake Model (Pinho, 2012) initiative, and are further described in the following sections.

Despite the large uncertainty and variability in the resulting loss estimations, the outcomes of the present study contribute to the understanding of the expected order of magnitude of human losses per country; the estimates are useful for large-scale risk mitigation campaigns or to raise seismic risk societal awareness.

## ESTIMATION OF GLOBAL HUMAN LOSSES

### Global Uniform Seismic Hazard Assessment

A globally homogeneous seismic hazard analysis is a prerequisite for the assessment of seismic risk. This requirement, however, presents many challenges that are not necessarily faced when attempting to determine seismic hazard on a local or regional scale. Homogeneity in the model does

not automatically follow from the data sets, as much of the earthquake data that is relevant for seismic hazard are not themselves globally homogeneous. The inhomogeneity comes from inability to establish uniform completeness across different earthquake catalogues, or our knowledge of the geometry and recurrence of active faults around the world, for example. A global appraisal of the current state of seismic hazard studies reveals diversity in methods and types of seismotectonic information used to construct the seismogenic sources and ground motion prediction models. Consequently, for use in the assessment of global risk, a patchwork of existing models may, in terms of losses, reflect differences in the knowledge and quality of the hazard model. To construct a global hazard map for use in global risk assessment we instead prefer to adopt an approach for characterization of the seismic source and ground motions prediction equations that is based on data that is global in spatial coverage, and of a sufficient degree of homogeneity as to allow hazard and risk in different parts of the world to be compared.

For the purposes of a global assessment of seismic risk, a preliminary global probabilistic seismic hazard analysis (PSHA) model is constructed using a smoothed seismicity-based seismogenic source model. Smoothed seismicity encompasses a family of algorithmic tools to characterize activity rate across a homogeneous grid by applying a bivariate smoothing kernel to the locations within a catalogue of earthquakes in order to characterize the uncertain contribution of each earthquake to each grid cell. This approach is common in the field of earthquake forecasting (e.g. Kagan and Jackson, 2012) and can inform the estimation seismic hazard (e.g. Frankel, 1995). The annual activity rate per $0.1^{o}$ by $0.1^{o}$ cell, derived using the kernel smoothing approach, is shown in Figure 1. These preliminary estimates could be further improved by incorporating the crustal fault database within the seismic source model to properly account for shaking estimates near the faults; especially the faults have potential to generate large damaging earthquakes.

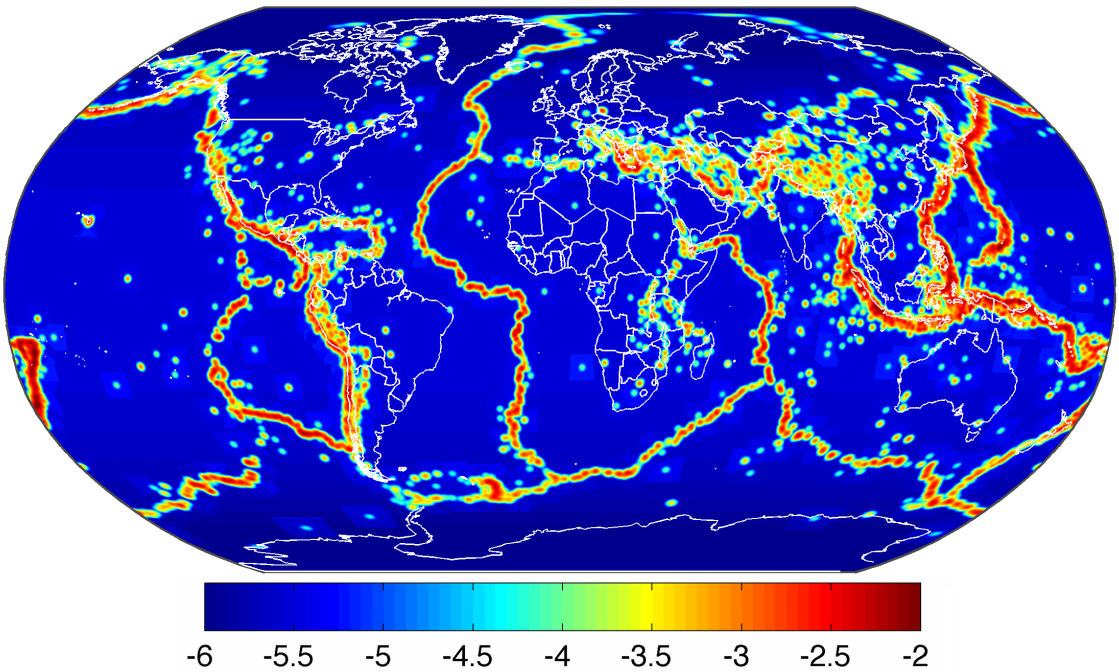


Figure 1. Activity Rate ($M \geq 5.0$ cell$^{-1}$ yr$^{-1}$) from the global smoothed seismicity model.

The initial step of the global smoothed seismicity hazard model is the construction of a global catalogue of instrumental and historical earthquakes for the period 1900 to 2012. The global catalogue is a composite of several bulletins including the ISC-GEM (Storchak et al., 2013), the ISC Reviewed Bulletin, the Global Centroid Moment Tensor catalogue and the Pacheco & Sykes (1992) bulletin. Common events amongst the catalogues are identified and the preferred hypocenter and magnitude are

selected according to a hierarchical preference scheme, thus ensuring that the preferred representation of each event is maintained in the homogenized catalogue. Before application of the smoothing kernel, the non-Poissonian events are removed from the catalogue and the spatio-temporal variation in completeness analyzed (See Weatherill and Pagani, 2014 for further details).

After consideration of several different smoothing kernels, it is found that a simple isotropic Gaussian kernel with a fixed bandwidth is sufficient to characterize the activity rate on a global 0.1˚ by 0.1˚ grid. Traditional kernel smoothing techniques have often failed to address issues such as variation in completeness and hypocentral depth distribution. We adjust for temporal variation in completeness by weighting earthquakes in each completeness period by their corresponding completeness durations. To take into account hypocentral depth distribution, for each event we distributed the 2-D spatial kernel through a set of depth layers using a truncated Gaussian cumulative distribution function, to ensure the kernel integrates to unity across the depth layers. In addition to the use of kernel smoothing for defining the activity rates within each cell, a smoothed focal mechanism algorithm is also implemented, adapting the approach proposed by Kagan and Jackson (2014). Consequently the high resolution global source model provides sufficient information, not only to constrain the activity rate in each cell, but the distribution through the depth layer and a set of conjugate fault planes that are consistent with the potential rupture orientations that may activate given the current stress conditions.

The global PSHA calculation is implemented using the OpenQuake-engine for seismic hazard and risk (Silva et al., 2013). A logic tree of ground motion predictions equations is used to model the epistemic uncertainty in the ground motion modeling. The logic tree largely implements the globally recommended set of GMPEs proposed by Stewart et al. (2014), albeit modifications are needed to account for tectonic region types not considered within their analysis (i.e. deep earthquakes in active continental regions, earthquakes in purely oceanic environments). For sites on a 0.1˚ resolution grid, a suite of hazard curves and hazard maps are calculated for PGA, Sa (0.2 s) and Sa (1.0), assuming a uniform site model (reference rock of $V_{S30}$ = 800 $ms^{-1}$). The hazard map for PGA with a 10 % probability of being exceeded in 50 years is shown in Figure 2. Further refinements and improvements to the model, including the incorporation of global subduction zone geometries, are now being implemented for future revisions of this global hazard model.

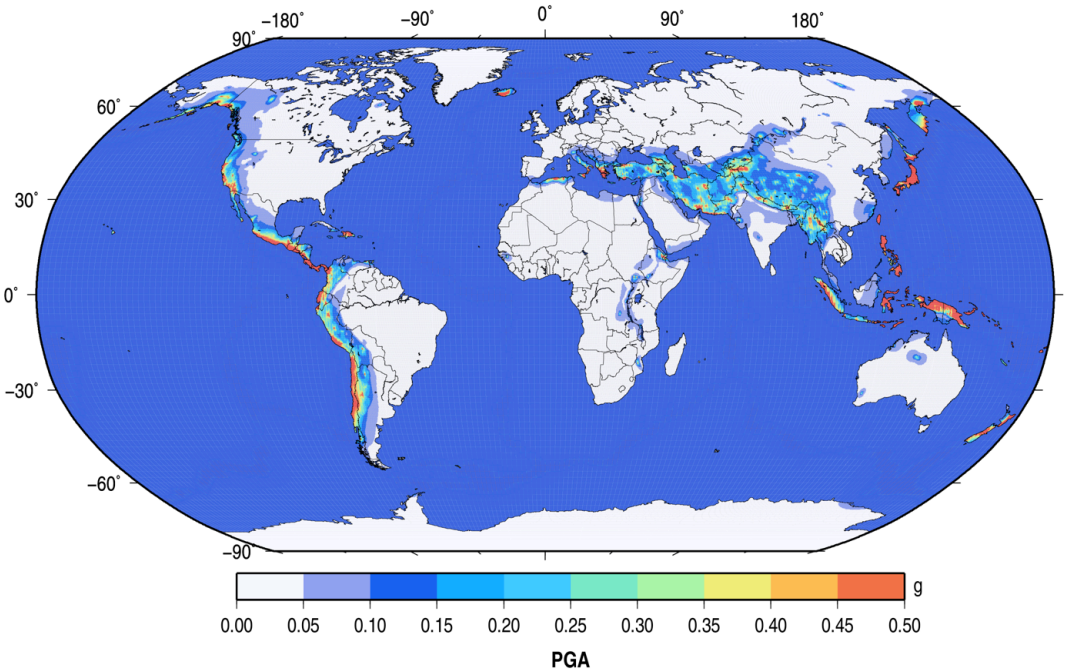


Figure 2. Preliminary mean global seismic hazard in terms of peak ground acceleration for a 10% probability of exceedance in 50 years.

A detailed description of the assumptions and methodologies employed in the development of this uniform seismic hazard model can be found in Weatherill et al. (2014). The work presented below is mainly focused on the estimation of human casualties, and not on the development of the hazard model.

## Consideration of Site Effects

Accounting for the effects of soil conditions that are different than the reference site model is of critical importance in seismic risk assessment, since ground motion amplification of upwards of a factor of two can be observed in regions composed by soft soils (Stewart *et al.*, 2013). The use of the average velocity of seismic shear waves in the top 30 meters layer ($V_{s30}$) is a common standard to characterize soil conditions, recognized by several design codes (e.g. BSSC, 2004; CEN, 2004). Furthermore, many ground motion prediction models (e.g. Atkinson and Boore, 2006; Chiou and Youngs, 2008) or site amplification methodologies (e.g. Borcherdt, 1994; Choi and Stewart, 2005) have been calibrated against seismic station site conditions described with $V_{s30}$ values.

The acquisition of $V_{s30}$ values at a large scale requires a significant investment of economic and human resources, and has only been done in few regions in the world (e.g. California (USA), Italy, Taiwan, southwest Portugal, Australia). The recognition these challenges has led to the development of simplified methodologies to derive first-order $V_{s30}$ values, mainly for the purposes of rapidly estimating post-earthquake human and economic losses (Jaiswal and Wald, 2013). Wills and Claham (2006) established a correlation between a set of geology units and $V_{s30}$ values for California, whilst Wald and Allen (2007) proposed a methodology that uses slope topography to obtain proxy $V_{s30}$ values, based on the assumption that stiffer materials (high-velocity) are more likely to maintain a steep slope while deep basin sediments are deposited mainly in environments characterized by a lower velocity. This approach has been subsequently revised in Allen and Wald (2009).

Whilst both methodologies seem to have a similar performance, the latter does not allow a uniform global application due to lack of datasets regarding geological characteristics, and the need of experts' intervention to correlate each geological unit with existing field measurements. Thus, in the present study a decision was made to follow the approach initially proposed by Wald and Allen (2007) to account for soils effects at a global scale. Nevertheless, it is important to recognize the large uncertainty associated with this methodology (Lemoine et al., 2012), and that alternative approaches to model site effects at a large scale should be investigated.

## Population Exposure Model

The most well known datasets capable of providing population count uniformly and globally at a fine spatial resolution are GRUMP and LandScan. GRUMP (Global Rural Urban Mapping Project) is produced by the Center for International Earth Science Information Network (CIESIN) and results from a combination of various datasets, such as national census, human settlements data (55,000), information from the City Population initiative, night-time lights, Digital Chart of the World, United Nations estimates, amongst others. It follows a 30 arc-second gridded resolution and the value assigned to each cell is an integer that represents the calculated population count. The latest version of GRUMP is for the year of 2000. Likewise, LandScan follows the same spatial distribution and uses some of the aforementioned datasets, in addition to VMap1 (a map of major roads and rail networks, drainage networks, utility systems, elevation contours, coastlines, international boundaries and populated places), Global Land Cover Characterization (GLCC) [6] and high-resolution aerial photography and satellite imagery. An algorithm is used to calculate a population likelihood coefficient, which is then combined with the expect amount of people for the associated region, leading to a population count per grid cell (Bhaduri et al., 2002). LandScan is frequently updated and its last version is for the year of 2012.

Despite the similarities between both datasets, LandScan provides more detailed data for some regions in the world (see Figure 3), and it has more up-to-date population estimates. For these reasons, the authors decided to employ the LandScan dataset in the assessment of the global fatalities.

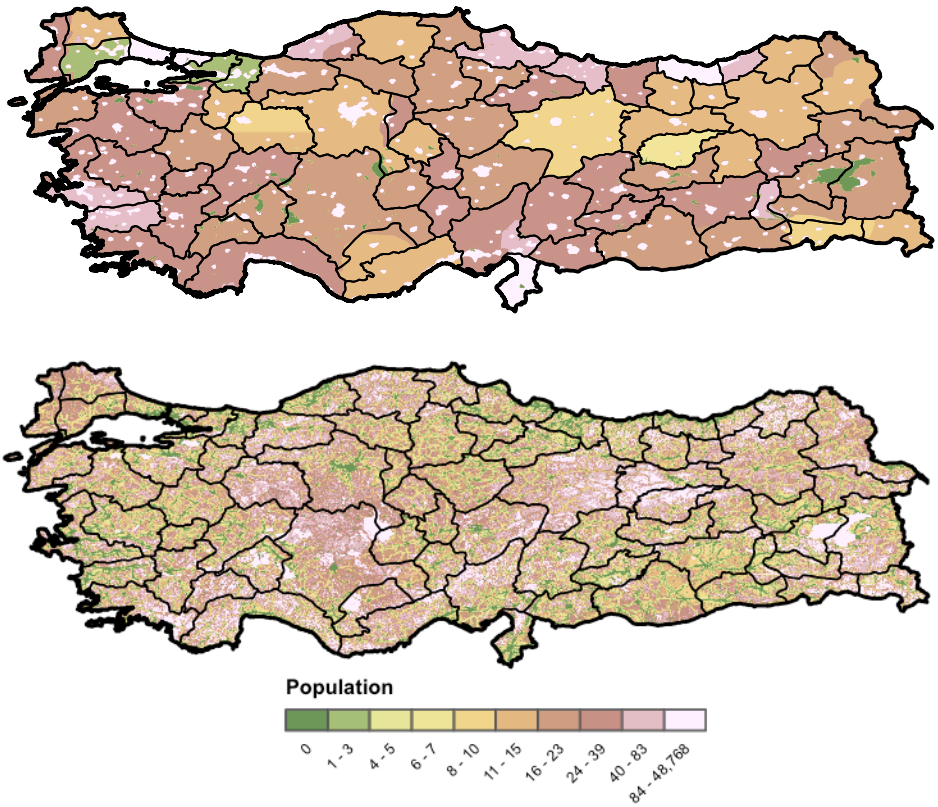


Figure 3. Population distribution in Turkey according to GRUMP (above) and LandScan (below).

## Country-based Empirical Vulnerability Model

In order to estimate long-term seismic risk in terms of potential human losses from an underlying seismic hazard, the country-based empirical vulnerability model developed by Jaiswal and Wald (2010) was used. This model is based on a comprehensive global catalogue of all significant worldwide earthquakes (M5.5 and above) since 1973. Thus, both fatal and non-fatal earthquakes are used to derive a set of empirical vulnerability functions that are capable of providing a fatality rate (the ratio of number of fatalities to the total population exposed at each level of shaking intensity) as a function of Modified Mercalli Intensity (MMI). A unique vulnerability function was derived for each country wherein 4 or more fatal earthquakes have occurred during the last 35+ years. For countries where empirical data was lacking, the authors proposed a globally consistent regionalization scheme based on a number of socio-economic indicators to relate the countries that share similar vulnerability traits. Regional vulnerability functions were developed considering earthquake events that have occurred in neighbouring countries. These relationships serve as a broader (country-specific), simplified approach to quantify aggregated earthquake losses, and bypasses the requirement of the detailed building type specific inventory, exposure and vulnerability/fragility data in order to perform loss/risk assessment for each geographic region of the world. Significant efforts are needed at regional and country levels to compile building damage, casualty and loss data from historical earthquakes in order to query these broad relationships, to validate their applicability in regional context, and to update them using available data.

## Loss Estimation Methodology

The loss assessment performed in this study follows a classical PSHA-based risk methodology, as described in Silva *et al*. (2013). In this process, the global seismic hazard model discussed in the

previous section is used to estimate sets of seismic hazard curves, in terms of rate of exceedance ($\lambda_{PGA}$) versus PGA. These curves are numerically estimated ($d\lambda_{PGA}(pga)/d(pga)$) to obtain the rate of occurrence of a large number of PGA values ($pga_j$).

These hazard curves have been estimated for bedrock ($V_{s30}$ = 800 m/s) and considering a 1-year investigation interval. Each value of PGA is modified in order to account for soil conditions, using the amplification factors proposed by Borcherdt (1994) and the local $V_{s30}$ value taken from the global $V_{s30}$ map server [7]. It is important to recognize that the consideration of soil conditions could have been performed by introducing the local $V_{s30}$ value directly in the ground motion prediction models (e.g. Chiou and Youngs, 2008; Akkar and Bommer, 2010). However, some attenuation models do not support multiple soil types (e.g. Toro et al., 2002) or use other parameters besides $V_{s30}$ to account for site effects (e.g. Zhao et al., 2006). Moreover, from a computational point of view it is significantly more efficient to modify rock-based hazard curves using Borcherdt (1994) approach only in the populated regions, rather than in every location where seismic hazard will be evaluated.

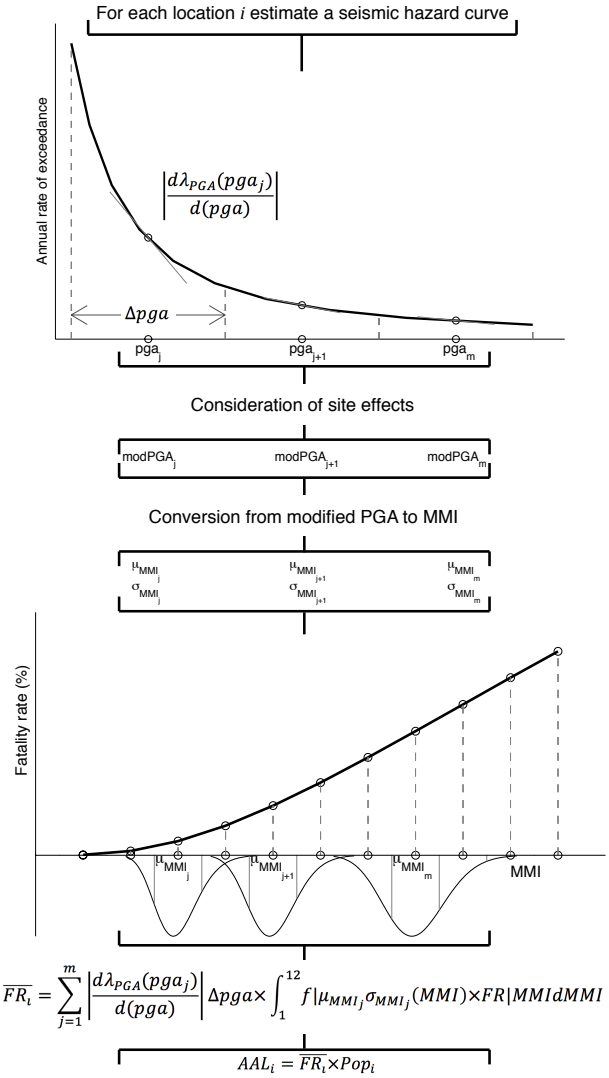


Figure 4. Representation of the process employed to estimate the average annual loss for each location.

Since the fatality vulnerability model uses MMI and the amplified ground motion is in terms of PGA, the intensity measure conversion equation proposed by Worden *et al*. (2012) was utilized. This conversion has a significant uncertainty associated, and thus for each PGA value, a mean MMI ($\mu_{MMI}$) and respective standard deviation ($\sigma_{MMI}$) are calculated and used to estimate a probability density function ($f|\mu_{MMI}\sigma_{MMI}$). This probability density function is combined with the vulnerability

function of the country of interest to calculate a conditioned fatality rate ($FR|\mu_{MMI}\sigma_{MMI}$). The annual fatality rate ($\overline{FR}$) is obtained by summing the product between each conditioned fatality rate and the respective rate of occurrence. This rate is multiplied by the number of people existing at the location of interest to attain the average annual fatalities ($AAL$). This process is repeated for every site where population exists (approximately 35 million locations), as schematically illustrated in Figure 4.

## PRELIMINARY SEISMIC RISK RESULTS

One important challenge that remains in front of us is how to portray and properly communicate the estimated seismic risk. Several maps showing the annualized expected fatalities, or human losses associated with certain predefined exceedance thresholds per country have been developed. In Figure 2, a preliminary global risk map showing variation of country mortality risk quantified in terms of average annual human losses is presented. It is worth noting that despite the high level of seismic hazard in the west coast of South America, the estimated seismic risk is not uniform and highly influenced by the vulnerability of built environment, e.g., countries like Ecuador, Peru, Venezuela share greater risk compared to Chile and Colombia.

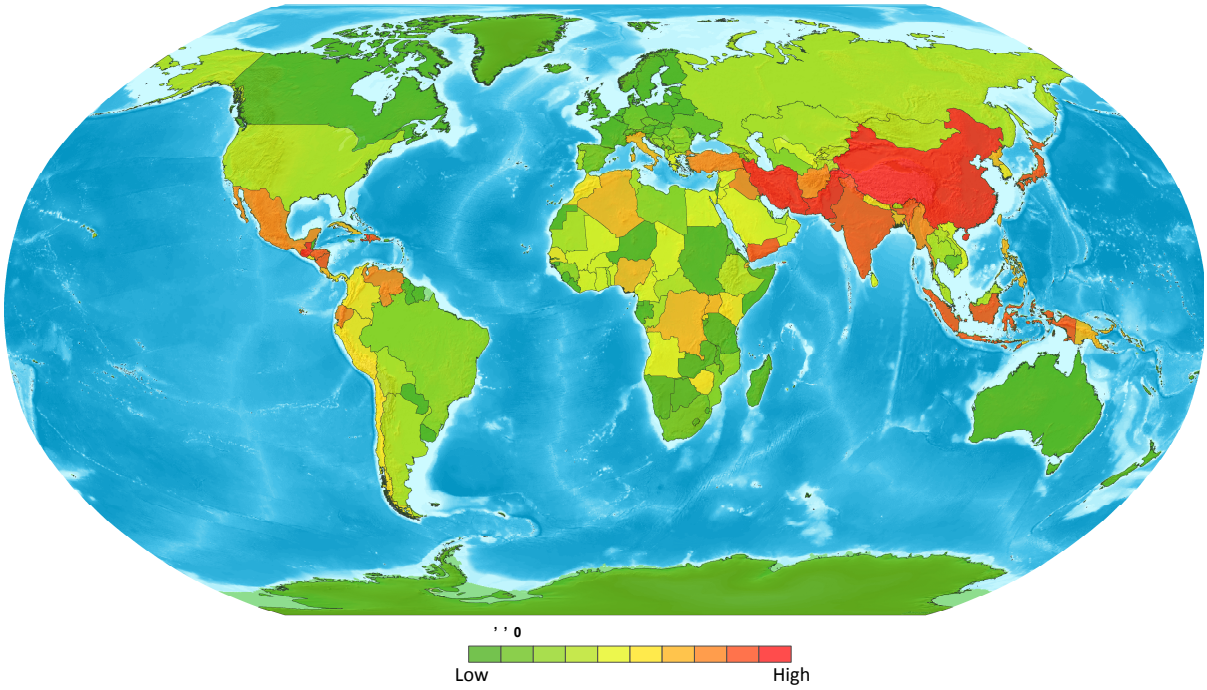


Figure 5. Preliminary global seismic risk map in terms of average annual human losses.

The results from Figure 2 also indicate many countries of the world such as China, India, Iran, Pakistan, and Indonesia that bear a disproportionate long-term seismic risk compared to others that may have comparable or higher earthquake shaking hazard. Quite unfortunately, these countries also happen to be the places where past earthquake risks' mitigation efforts have not been highly effective, as witnessed based on the effects of recent earthquakes that have occurred there. Additionally, most of the new highly-populated cities (population in excess of 1 million) are located in these countries.

## CONCLUSIONS

In the present study, a comprehensive earthquake loss assessment has been carried out at a global scale, resulting in human loss maps for different return periods and a set of country-based average annual human losses. For this purpose, a number of global, uniform and publically available datasets have been explored to derive a uniform probabilistic seismic hazard and risk model. It has been estimated that at least 45% of the world population is exposed to a perceivable seismic hazard (PGA of 0.05g in 475 years), and 25% to a level of hazard capable of causing human losses (PGA of 0.1g in 475 years). The evaluation of the global distribution of human losses reveals alarming levels of fatalities, even for countries that have not suffered fatal events in the recent past (e.g. Cyprus, Dominica). Despite the large uncertainty and variability in the resulting loss estimations, the outcomes of the present study contribute to the understanding of the expected order of magnitude of human losses per country, which are useful for large-scale risk mitigation campaigns, to raise seismic risk societal awareness, or to highlight the regions of the world that are more prone to human losses, and thus where aid should be prioritized.

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