Hazard Specific Risk Assessment: Geophysical

1 - Earthquake Hazard and Risk Assessment

Key words: vulnerability function, probabilistic seismic hazard analysis (PSHA), ground motion prediction equation (GMPE), exposure model, seismic hazard map

The uncontrolled growth of the global population has led to an increase of the annual losses from 14 billion USD in 1985 to more than 140 billion USD in 2014. Similarly, the average affected population has risen from 60 million to over 179 million within the same period[1]. Earthquakes constitute approximately one fifth of the annual losses due to natural disasters, with an average death toll of over 25 thousand people per year[2]. The assessment of earthquake risk constitutes the first step to support decisions and actions to reduce the potential losses due to earthquakes. This process involves the development of seismic hazard models characterizing the level of ground shaking and its associated frequency across a region, exposure datasets defining the geographic location and value of the elements exposed to the hazards, and vulnerability functions establishing the likelihood of loss conditional on the shaking intensity. Risk metrics can support decision makers in the development of risk reduction measures, which can include emergency response plans, enforcement of design codes, creation of retrofitting campaigns, urban planning or development of insurance pools.

Global seismic activity

The majority of the earthquakes are generated at boundaries where plates converge, diverge or move laterally past one another[3]. The greatest proportion of seismicity occurs in regions where lithospheric plates converge with one another. These convergent boundaries may manifest as regions of subduction, where oceanic crust is forced down beneath either the continental plate (e.g. west coast of South America) or of younger oceanic crust. Convergent boundaries may also produce regions of continental collision resulting in tectonic compression (e.g. Himalaya). Both types of environments are characterized by regions of high seismic activity, and host faults capable of generating very large earthquakes. Divergent plate boundaries represent areas where shallow crust is being pulled apart. These may manifest as rift zones (e.g. east African Rift), where the shallow continental crust is undergoing extension, resulting in moderate to high seismicity. Transform and transcurrent plate boundaries manifest where the relative movement of plates is lateral (e.g. San Andreas Fault in California). Due to their proximity to many large urban centres, these systems can pose a significant threat to society (e.g. Istanbul). The global distribution of earthquakes between 1900 and 2014, as well as the main plate boundaries are illustrated in Figure 1.

Records of seismic events throughout history are fundamental to our understanding of the earthquake process. Systematic recording of seismic waves using more precise seismometry began at the end of the 19th century. The modern era of instrumental seismology was transformed, however, in the early 1960s with the establishment of the World-Wide Network of Seismograph Stations, which deployed over 120 continuously recording stations. The International Seismological Centre (ISC) maintains the most comprehensive bulletin of parameterized seismic events since 1964. The ISC bulletin defines the location and size of earthquakes from an integrated network of approximately 14,500 seismic stations.[4]

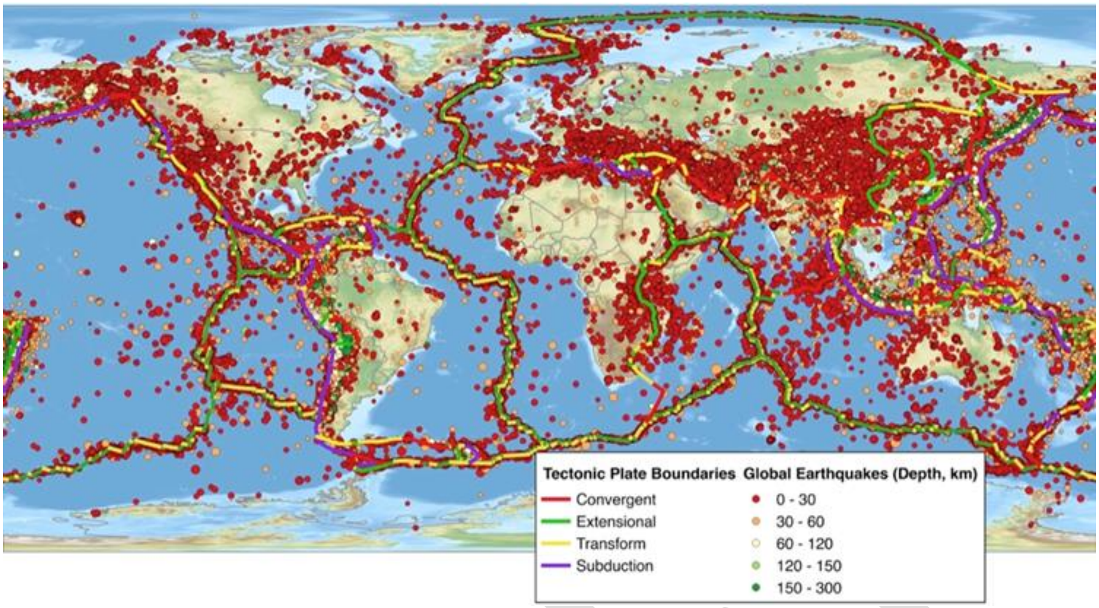

FIGURE 1 - The global distribution of earthquakes in the period 1900 CE to 2014 CE[4,5] and global plate boundaries[3]

Seismic hazard assessment

Seismic hazard assessment allows the calculation of the likelihood of ground shaking across a region, which is a fundamental component in seismic risk assessment or hazard mapping for design codes. This process may require several components, such as earthquake catalogues (historical and instrumental), active geological faults, geodetic estimates of crustal deformation, seismotectonic features and paleoseismicity. Seismic hazard may be analysed in two main ways: deterministically, in which a single (usually) most adverse seismic scenario is identified, or probabilistically, in which all-potential earthquake scenarios are explicitly considered along with their likelihood of occurrence. Deterministic approaches may be perceived as conceptually simpler and more conservative. The development of a probabilistic seismic hazard analysis (PSHA) model requires complex mathematical formulations to account for uncertainties in earthquake size, location, and time of occurrence, and the outputs relate various levels of ground shaking that may be observed at a site with a corresponding exceedance probability in a given time period. This relation between ground shaking and probability constitute a hazard curve. The expected ground shaking for a probability of exceedance within a time span (e.g. 10% in 50 years) or a return period (e.g. 475 years) can be calculated for a given region, leading to a hazard map. A fault dataset, an earthquake catalogue, and a seismic hazard map for a return period of 475 years are presented for the country of Colombia in Figure 2.

Since its inception by Cornell (1968)[6] and McGuire (1976)[7], several critical developments can be identified such as the complex representation of seismic source, the derivation of new models to describe the recurrence of earthquake, sophisticated ground motion prediction equations (GMPE), and employment of logic threes for the propagation of epistemic uncertainties[8]. Probabilistic seismic hazard analyses typically follow two main approaches: time-independent - incorporating geological and geodetic evidence with both instrumental and historical earthquake catalogues to derive a seismogenic model covering earthquake cycles up to thousands of years; and time-dependent – which accounts for periodic trends in earthquake recurrence to predict the likelihood of earthquakes occurring in a source given the time elapsed since the previous event.

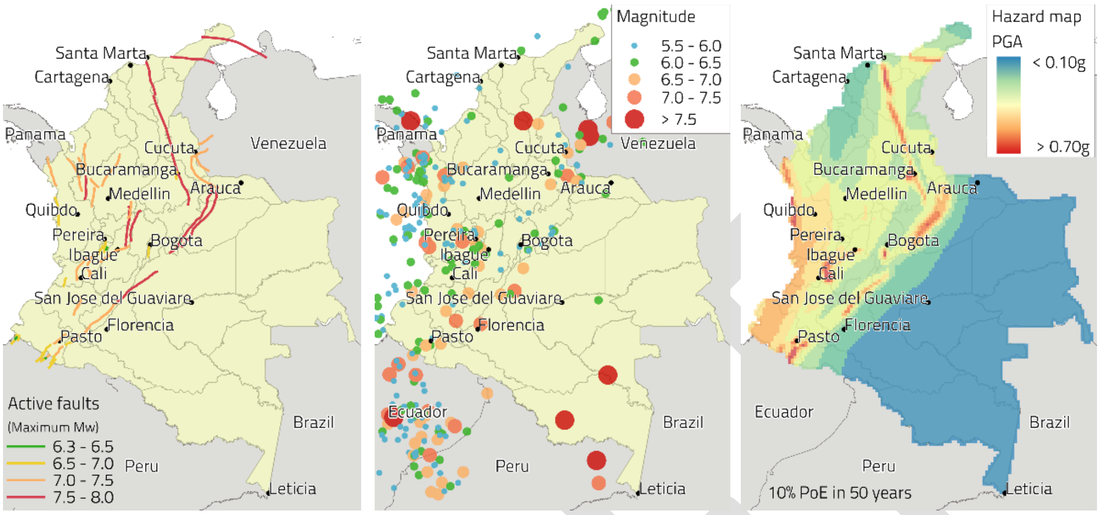

FIGURE 2 – Fault dataset (left), earthquake catalogue (centre) and seismic hazard map (right) in terms of peak ground acceleration for a return period of 475 years for Colombia[9]

The later approach requires detailed information concerning the past seismicity in the region, and therefore application of time-dependent seismic hazard analysis is still limited to only a few places in the world with well-studied active faults (e.g. California, Japan). Various software packages are available for the calculation of seismic hazard using deterministic or probabilistic approaches. OpenQuake[10] is one of such packages, and was adopted in recent regional projects for seismic hazard assessment in Europe, the Middle East, Latin America, the Caribbean and Africa.

Assessment of earthquake expected losses

The assessment of the impact from single seismic events represents a useful tool for the development of risk reduction measures. For example, Anhorn and Khazai (2014)[11] investigated the need for shelter spaces in Kathmandu (Nepal) considering several destructive earthquakes. Mendes-Victor et al. (1994)[12] and ERSTA (2010)[13] estimated the expected losses in the city of Lisbon and Algarve (Portugal) for strong seismic events, respectively. These results were used by the National Authority for Civil Protection to develop emergency response plans.

This analysis requires the definition of an earthquake rupture, which can be a hypothetical event (defined based on historical earthquakes or a PSHA model[14 15]) or a recent earthquake (whose parameters can be computed using inversion analyses[16]). In the former approach, the ground shaking is calculated using one or multiple GMPEs. In the latter case, the ground shaking can be calculated using GMPEs and recordings from seismic stations[17]. In general, this distribution of ground shaking can be used to calculate damage or losses, using an exposure model and a set of fragility or vulnerability functions. An exposure model describes the spatial distribution of the elements exposed to the hazards, as well their value and vulnerability class.[29 18] A fragility function establishes the probability of exceeding a number of damage states conditional on a set of ground shaking levels, whilst a vulnerability function relates the probability of loss ratio for a set of ground shaking levels.[19] [20] The ground shaking, exposure model and fragility/vulnerability functions can be combined to calculate the distribution of damage or losses[21], as illustrated in Figure 3 for a region around the capital of Colombia, Bogota.

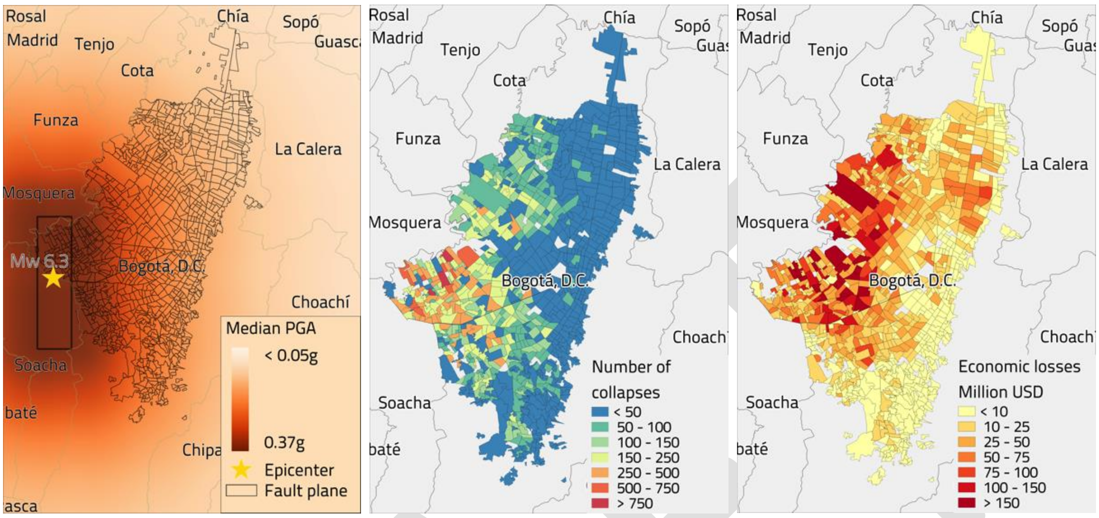

FIGURE 3 – Mean ground shaking in terms of peak ground acceleration for a M6.5 event west of Bogota (left), and resulting mean number of collapses (centre) and mean economic losses (right)

Certain risk reduction measures may require the consideration of all of the possible earthquake scenarios along with their frequency of occurrence which can be developed using probabilistic modelling. For example, these analyses can enable the prioritization of regions or building classes in need for risk reduction interventions. Valcárcel et al. (2013)[22] explored this type of analysis to assess the effectiveness of seismic retrofitting of schools in South and Central America. A probabilistic earthquake risk model was used to calculate the expected annual losses considering the portfolio of schools, and the savings due to the implementation of retrofitting or rebuilding interventions. Another risk reduction measure that requires a probabilistic approach is the creation of insurance pools. These financial mechanisms reduce the economic burden of the reconstruction from local governments and householders, by transferring the financial risk to the international insurance market. The Turkish Catastrophe Insurance Pool (TCIP) is a good example of such risk reduction measure.[23] This effort was developed after the Kocaeli and Düzce earthquakes in 1999, whose reconstruction costs had to be covered mostly by the Turkish government. These additional funds can also reduce the time to recover from the earthquake.

For this type of analysis it is necessary to employ a PSHA model, as described in the previous section. This model can be used to generate large sets of stochastic events, each representing a possible realization of the seismicity within a given time span (e.g. 10,000 years). For each event, several GMPEs can be employed to calculate the spatial distribution of the ground shaking at the location of the assets within the exposure models. Then, using the set of vulnerability functions, the losses for the entire portfolio are calculated. This distribution of losses can be employed to calculate the average annual losses or the aggregated losses for specific return periods.[24] These metrics can be compounded with the local socio-economic conditions in order to provide a holistic representation of the earthquake risk.[25] [26] [27] To this end, the risk metrics can be aggravated or attenuated according to a social vulnerability index. This index is derived considering a large number of socio-economic indicators such as education, poverty, crime, age or unemployment.

An exposure model for the residential building stock is presented in Figure 4 for the country of Colombia, along with the associated average annual economic losses and socio-vulnerability index at the second administrative level. Such calculations can be performed using the OpenQuake-engine[28] from the Global Earthquake Model.

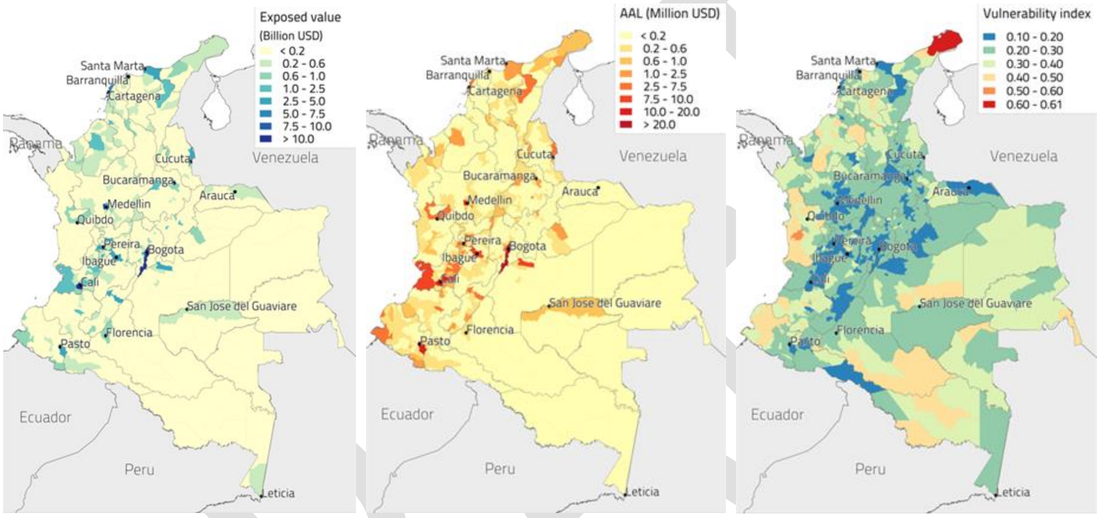

FIGURE 4 – Exposure model (left), average annual economic losses (centre) and socio-economic vulnerability index (right) for the residential building stock in Colombia[18] [29]

Conclusion

Earthquake can cause large economic and human losses, and represent a serious impediment to socio-economic development, creation of jobs and availability of funds for poverty reduction initiatives. Seismic hazard and risk assessment are fundamental tools in the development of risk reduction measures. This process involves the collection of earthquake catalogues and fault data, development of seismogenic models, selection of ground motion prediction equations, creation of exposure models and derivation of sets of fragility or vulnerability functions. The combination of these components for the assessment of seismic hazard and risk require complex software packages, some of which are currently publically available. Several examples around the world have demonstrated how seismic hazard and risk information can be used to develop risk reduction measures, and ultimately mitigate the adverse effects of earthquakes.

Authors: Vitor Silva, Catalina Yepes-Estrada, Graeme Weatherill (Global Earthquake Model Foundation)

Contributors and Peer Reviewers: Carmine Galasso (University College London)

☑ Peer reviewed
☐ Edited

---

[1] GFDRR. 2016. The making of a riskier future: How our decisions are shaping future disaster risk. World Bank publication, Washington DC, USA.

[2] EM-DAT. 2017. http://www.emdat.be/ (accessed on the 24th of January 2017).

[3] Bird P. 2003. An updated digital model of plate boundaries. Geochemistry, Geophysics, Geosystems, G3, 4(3) doi:10.1029/2001GC000252.

[4] Storchak D, Di Giacomo D, Endgdahl E, Harris J, Bondár I, Lee W, Bormann P, Villaseñor A. 2015. The ISC-GEM Global Instrumental Earthquake Catalogue (1900 - 2009): Introduction. Physics of the Earth and Planetary Interiors 239: 48–63.

[5] Weatherill G, Pagani M, Garcia J. 2016. Exploring Earthquake Databases for the Creation of Magnitude-Homogeneous Catalogues: Tools for Application on a Regional and Global Scale. Geophysical Journal International, 206(3):1652–76.

[6] Cornell C. 1968. Engineering seismic risk analysis. Bulletin of the Seismological Society of America, 58:1583-1606.

[7] McGuire R. 1976. Fortran program for seismic risk analysis. U.S. Geological Survey Open-File Report 76–67.

[8] Bommer J, Scherbaum F. 2008. The Use and Misuse of Logic Trees in Probabilistic Seismic Hazard Analysis, Earthquake Spectra, 24: 997-1009.

[9] Garcia J, Weatherill G, Pagani M, Rodriguez L, Poggi V, and the SARA hazard team. 2017. Building an open seismic hazard model for South America: the SARA-PSHA model. Proceedings 16th World Conference On Earthquake Engineering, 9-13 January 2017, Santiago, Chile.

[10] Pagani M, Monelli D, Weatherill G, Danciu L, Crowley H, Silva V, Henshaw P, Butler L, Nastasi M, Panzeri L, Simionato M, Vigano D. 2014. OpenQuake Engine: An open hazard (and risk) software for the Global Earthquake Model. Seismological Research Letters, 85(3):692-702.

[11] Anhorn J, Khazai B. 2014. Open space suitability analysis for emergency shelter after an earthquake. Natural Hazards and Earth System Sciences Discussions, 1(2):4263-4297.

[12] Mendes-Victor L, Oliveira C, Pais I, Teves-Costa P. 1994. Earthquake damage scenarios in Lisbon for disaster preparedness. In: Tucker BE, Erdik M, Hwang CN (eds) Issues in urban earthquake risk. NATO ASI series E, Applied Science, vol 271. Dordrecht, Kluwer Academic Press, pp 265–289.

[13] ERSTA. 2010. Estudo do risco sísmico e de tsunamis do Algarve. ISBN: 978-989-8343-06-2. Autoridade Nacional de Protecção Civil, Carnaxide, Portugal (in Portuguese).

[14] Bendimerad F. 2001. Loss estimation: a powerful tool for risk assessment and mitigation. Soil Dynamics and Earthquake Engineering, 21(5):467-472.

[15] Ansal A, Akinci A, Cultrera G, Erdik M, Pessina V, Tonuk G, Ameri G. 2009. Loss estimation in Istanbul based on deterministic earthquake scenarios of the Marmara Sea region (Turkey). Soil Dynamics and Earthquake Engineering, 29:699–709.

☑ Peer reviewed
☐ Edited

---

[16] Ji C, Wald D., Helmberger D. 2002. Source description of the 1999 Hector Mine, California earthquake; Part I: Wavelet domain inversion theory and resolution analysis. Bulletin of the Seismological Society of America, 92(4):1192-1207.

[17] Worden B., Wald D. 2016. ShakeMap Manual. USGS Technical Report, dx.doi.org/10.5066/F7D21VPQ.

[18] Yepes-Estrada C., Silva V., Valcárcel J., Acevedo A., Hube M., Coronel G., Santa Maria H. 2017. A Uniform Residential Building Inventory for South America. Earthquake Spectra. doi: 10.1193/101915EQS155DP.

[19] Rossetto T., Ioannou I., Grant D. 2015. Existing Empirical Fragility and Vulnerability Functions: Compendium and Guide for Selection (GEM Technical Report). Pavia, Italy: GEM Foundation. doi:10.13117/GEM.VULNSMOD.TR2015.01.

[20] D'Ayala D., Meslem A., Vamvatsikos D., Porter K., Rossetto T. 2015. Guidelines for analytical vulnerability assessment of low/mid-rise buildings. GEM Technical Report 2015-08 v1.0.0, GEM Foundation, Pavia, Italy. doi: 10.13117/GEM.VULN-MOD.TR2014.12.

[21] Silva V. 2016 Critical Issues in Earthquake Scenario Loss Modeling. Journal of Earthquake Engineering.

[22] Valcárcel J.A, Mora M.G, Cardona O.D., Pujades L.G., Barbat A., Bernal G. 2013. Methodology and applications for the benefit cost analysis of the seismic risk reduction in building portfolios at broadscale. Natural Hazards 69: 845. doi:10.1007/s11069-013-0739-2.

[23] Bommer J., Spence R., Erdik M., Tabuchi, S., Aydinoglu N., Booth E., Re D., Pterken D.. 2002. Development of an Earthquake Loss Model for Turkish Catastrophe Insurance. Journal of Seismology, 6:431-446.

[24] Silva V. 2017. Critical Issues in Probabilistic Seismic Risk Analysis. Journal of Earthquake Engineering.

[25] Carreño L., Cardona O., Barbat A. 2007. Urban seismic risk evaluation: a holistic approach. Natural Hazards, 40:137-172.

[26] Khazai B., Bendimerad F. 2011. Risk and resiliency indicators, EMI Topical Report 565 TR-1 03.

[27] Burton C., Silva V. 2016. Assessing Integrated Earthquake Risk in OpenQuake with an Application to Mainland Portugal. Earthquake Spectra, 32(3):1383-1403.

[28] Silva V., Crowley H, Pagani M., Monelli D., Pinho R.. 2014. Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment. Natural Hazards, 72(3):1409-1427.

[29] Yepes-Estrada C., Silva V.. 2017. Probabilistic seismic risk assessment of the residential building stock in South America. Proceedings 16th World Conference On Earthquake Engineering, 9-13 January 2017, Santiago, Chile.

☑ Peer reviewed
☐ Edited