Words into Action Guidelines:
National Disaster Risk Assessment
Hazard Specific Risk Assessment

1. Earthquake Hazard and Risk Assessment

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

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The uncontrolled growth of the global population led to an increase in annual earthquake-related losses from US$ 14 billion in 1985 to more than US$ 140 billion in 2014. Similarly, the average affected population rose 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 25,000 people per year.[2]

Earthquakes may cause liquefaction, landslides, fire, and tsunami which would lead to far higher level of damage and losses. This module is focused on assessing only earthquake shaking hazard and risk. The assessment of earthquake risk constitutes the first step to support decisions and actions to reduce potential losses. The process involves developing (a) earthquake hazard models characterizing the level of ground shaking and its associated frequency across a region, (b) exposure data sets defining the geographic location and value of the elements exposed to the hazards and (c) vulnerability functions establishing the likelihood of loss conditional on the shaking intensity.

Risk metrics can support decision makers in developing risk reduction measures that can include emergency response plans, the enforcement of design codes, the creation of retrofitting campaigns and development of insurance pools.

Global earthquake activity

Most earthquakes are generated at boundaries where plates converge, diverge or move laterally past one another[3]. The greatest amount of seismicity occurs in regions where lithospheric plates converge. 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. the Himalayas).

Both types of environments are characterized by regions of high earthquake 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). Because of their proximity to many large urban centres, these systems can pose a significant threat to society (e.g. Istanbul). Figure 1

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1 Global Facility for Disaster Reduction and Recovery. The Making of a Riskier Future: How Our Decisions are Shaping Future Disaster Risk. Washington D.C.: World Bank.

2 EM-DAT (Emergency Events Database) (2017). www.emdat.be (last accessed on 24 Jan. 2017).

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

illustrates the global distribution of earthquakes between 1900 and 2014, as well as the main plate boundaries.

Records of earthquake events throughout history are fundamental to our understanding of the earthquake process. Systematic recording of earthquake waves using more precise seismometry began at the end of the nineteenth 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 maintains the most comprehensive bulletin of parameterized earthquake events since 1964. The bulletin defines the location and size of earthquakes from an integrated network of approximately 14,500 earthquake stations.[4]

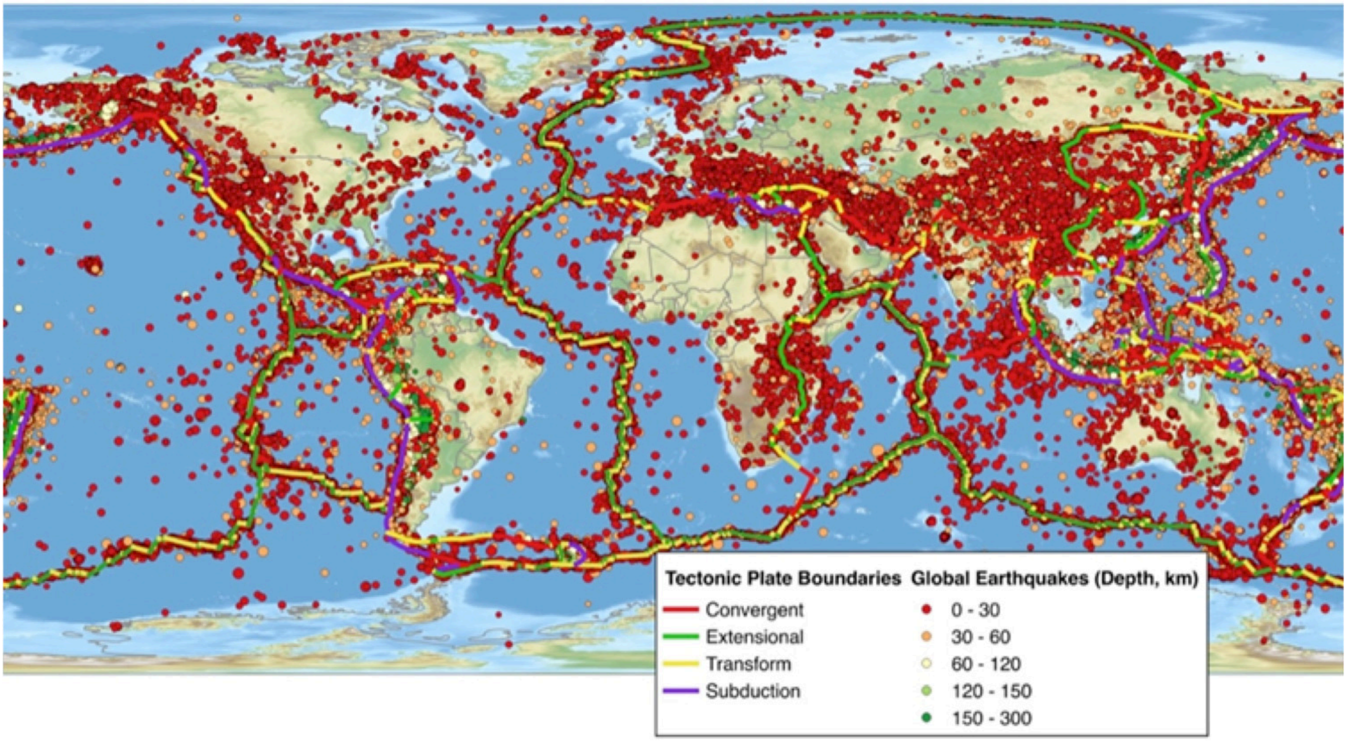

Figure 1 - The global distribution of earthquakes in the period from 1900 to 2014, and global plate boundaries

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[4] Storchak, D. and others (2015). The ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009): Introduction. Physics of the Earth and Planetary Interiors, vol. 239, pp. 48-63.

[5] Weatherill, G, M. Pagani and J. Garcia (2016). Exploring earthquake databases for the creation of magnitude-homogeneous catalogues: tools for application on a regional and global scale. Geophysical Journal International, vol. 206, issue 3, pp.1652-1676.

Earthquake hazard assessment

Earthquake hazard assessment enables the likelihood of ground shaking across a region to be calculated, which is a fundamental component in earthquake risk assessment or hazard mapping for design codes. The process may require several components, such as earthquake catalogues (historical and instrumental), active geological faults, geodetic estimates of crustal deformation, seismotectonic features and paleoseismicity.

Earthquake hazard may be analysed in two main ways: deterministically, in which a single (usually) most adverse earthquake 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 earthquake 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 constitutes a hazard curve. The expected ground shaking for a probability of exceedance within a time span (e.g. 10 per cent in 50 years) or a return period (e.g. 475 years) can be calculated for a given region, leading to a hazard map. Figure 2 shows a fault data set, an earthquake catalogue and a earthquake hazard map for a return period of 475 years for Colombia.

Since the inception of PSHA by Cornell (1968)[6] and McGuire (1976)[7], several critical developments can be identified such as the complex representation of the earthquake source, the derivation of new models to describe the recurrence of earthquakes, sophisticated ground motion prediction equations (GMPE) and the use of logic trees for the propagation of epistemic uncertainties.[8]

Probabilistic earthquake hazard analysis typically follows 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 – accounting for periodic trends in earthquake recurrence to predict the likelihood of earthquakes occurring in a source given the time elapsed since the previous event.

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[6] Cornell, C. (1968). Engineering seismic risk analysis. *Bulletin of the Seismological Society of America*, vol. 58, pp.1583-1606.

[7] McGuire, R. (1976). FORTRAN computer program for seismic risk analysis. *United States Geological Survey open-file report*, pp. 76-67.

[8] Bommer, J. and F. Scherbaum (2008). The use and misuse of logic trees in probabilistic seismic hazard analysis. E*arthquake Spectra,* vol. 24, pp. 997-1009.

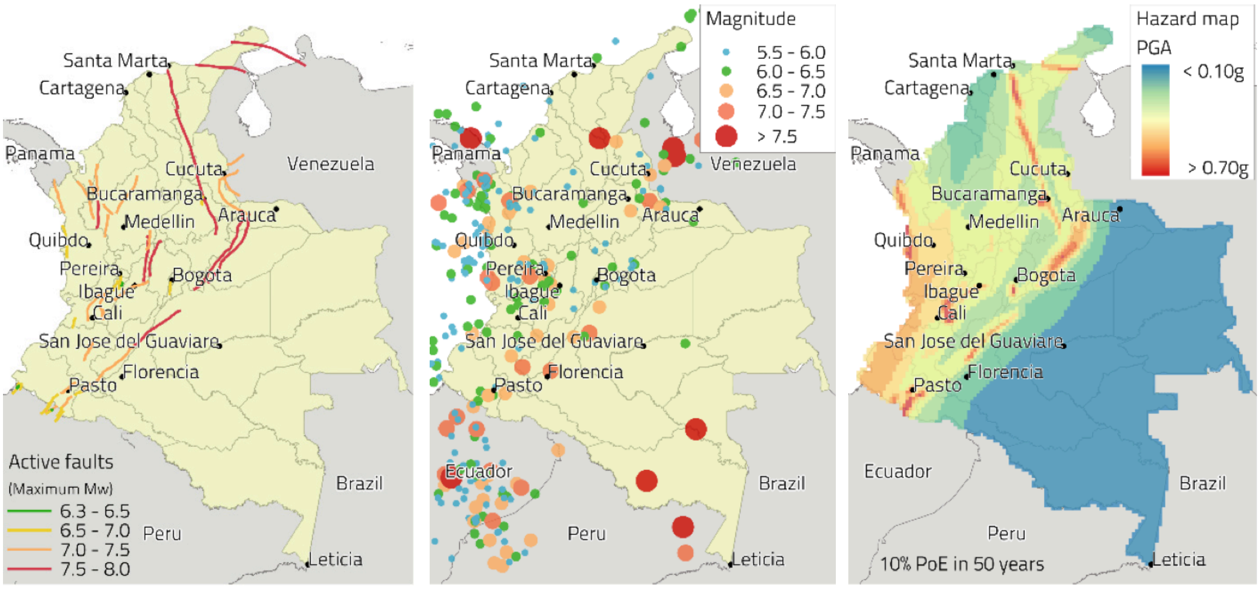

Figure 2 – Fault data set (left), earthquake catalogue (centre) and earthquake hazard map (right) in terms of peak ground acceleration for a return period of 475 years for Colombia[9]

As time-dependent approach requires detailed information concerning the past earthquakeity in the region andfault rupture history application of time-dependent earthquake 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 calculating earthquake hazard using deterministic or probabilistic approaches. OpenQuake[10] is one such package and has been adopted in recent regional projects for earthquake hazard assessment in Europe, the Middle East, Latin America, the Caribbean and Africa.

Assessment of earthquake expected losses

Carrying out an assessment of the impact of single earthquake events (deterministic approach) is a useful tool for developing risk reduction measures. For example, Anhorn and Khazai (2014)[11] investigated the need for shelter spaces in Kathmandu (Nepal) considering several destructive

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[9] Garcia, J. and others (2017). Building an open seismic hazard model for South America: the SARA-PSHA model. Proceedings of the 16th World Conference on Earthquake Engineering, 9-13 January 2017, Santiago.

10 Pagani, M. and others (2014). OpenQuake engine: an open hazard (and risk) software for the Global Earthquake Model. *Seismological Research Letters*, vol. 85, issue 3, pp. 692-702.

11 Anhorn, J. (2014). Open space suitability analysis for emergency shelter after an earthquake. *Natural Hazards and Earth System Sciences Discussions,* vol. 1, issue 2, pp. 4263-4297.

earthquakes. Mendes-Victor et al. (1994)[12] and the Portuguese National Civil Protection Authority (2010)13 estimated the expected losses in Lisbon and the Algarve (Portugal), respectively, for strong earthquake events. The National Civil Protection Authority used these results 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, the ground shaking can be calculated using GMPEs and recordings from earthquake 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 as their value and vulnerability class.18 A fragility function establishes the probability of exceeding a number of damage states conditional on a set of ground shaking levels, whereas 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 Bogotá, Colombia.

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12 Mendes-Victor, L. and others (1994). Earthquake damage scenarios in Lisbon for disaster preparedness. In: Tucker B.E., M. Erdik and C.N Hwang, eds. Issues in urban earthquake risk. NATO ASI series E, *Applied Science*, vol. 271, pp. 265-289. Dordrecht: Kluwer Academic Press.

13 National Civil Protection Authority (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*, vol. 21, issue 5, pp. 467-472.

15 Ansal, A. and others (2009). Loss estimation in Istanbul based on deterministic earthquake scenarios of the Marmara Sea region (Turkey). *Soil Dynamics and Earthquake Engineering*, vol. 29, pp. 699-709.

16 Ji, C., D. Wald and D. Helmberger (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,* vol. 92, issue 4, pp. 1192-1207.

17Worden, B. and D. Wald (2016). *ShakeMap Manual.* United States Geological Survey technical report, dx.doi.org/10.5066/F7D21VPQ.

18 Yepes-Estrada, C. and others (2017). A uniform residential building inventory for South America. *Earthquake Spectra*. doi: 10.1193/101915EQS155DP.

19 Rossetto, T., I. Ioannou and D. Grant (2015). Existing Empirical Fragility and Vulnerability Functions: Compendium and Guide for Selection. *Global Earthquake Model (GEM) technical report. Pavia, Italy*: GEM Foundation. doi:10.13117/GEM.VULNSMOD.TR2015.01.

20 D'Ayala, D. and others (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*, vol. 20, issue 8, pp.1322-1341.

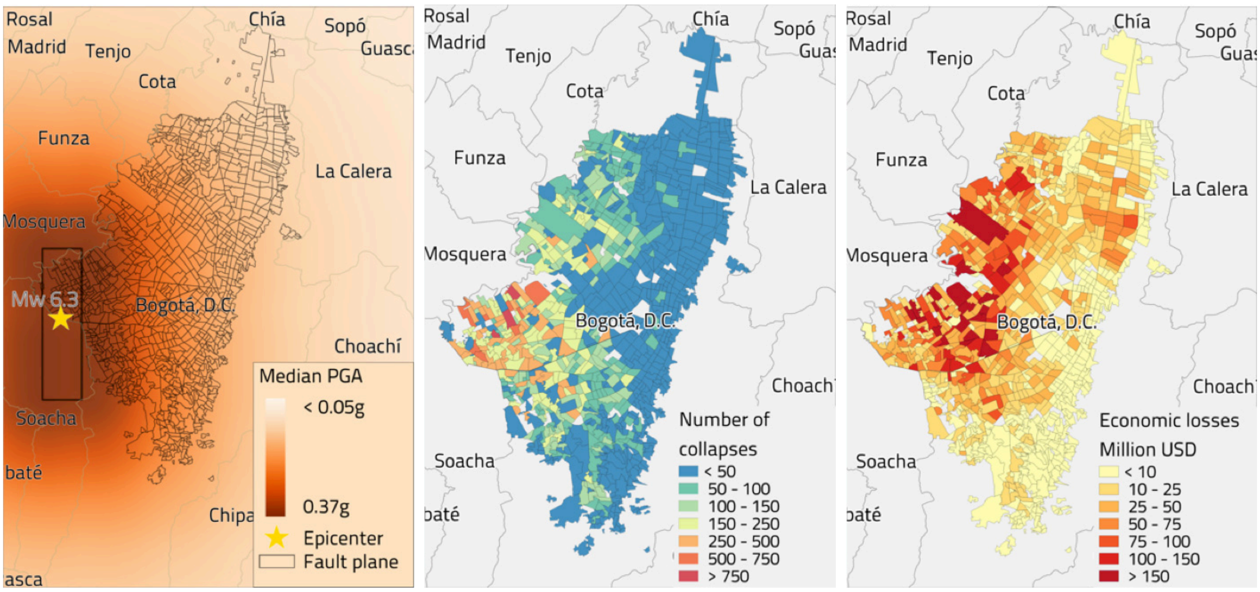

Figure 3 – Mean ground shaking in terms of peak ground acceleration for a M6.5 event west of Bogotá (left), and resulting mean number of collapses (centre) and mean economic losses (right)

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 of risk reduction interventions. Valcárcel et al. (2013)[22] explored this type of analysis to assess the effectiveness of the earthquake retrofitting of schools in South and Central America. They used a probabilistic earthquake risk model to calculate the expected annual losses considering the portfolio of schools and the savings as a result of the 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 on local governments and householders by transferring the financial risk to the international insurance market. A good example of such a measure is the Turkish Catastrophe Insurance Pool (TCIP).[23] It was created after the Kocaeli and Düzce earthquakes in 1999, following which the reconstruction costs had to be covered mostly by the Government. These additional funds can also reduce the time to recover from the earthquake.

PSHA 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 used 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

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[22] Valcárcel, J.A. and others (2013). Methodology and applications for the benefit cost analysis of the seismic risk reduction in building portfolios at broadscale. *Natural Hazards,* vol. 69, issue 1, pp. 845-868. doi:10.1007/s11069-013-0739-2.

[23] Bommer, J. and others (2002). Development of an earthquake loss model for Turkish Catastrophe Insurance. *Journal of Seismology,* vol. 6, pp. 431-446.

losses for the entire portfolio can be calculated. This distribution of losses can be used to calculate the average annual losses or the aggregated losses for specific return periods.[24]

These metrics can be compounded with the local socioeconomic 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. The index is derived from a large number of socioeconomic indicators such as education, poverty, crime, age or unemployment.

Figure 4 presents an exposure model for the residential building stock for 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 engine28 from the Global Earthquake Model.

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24 Silva, V. (2017). Critical issues in probabilistic seismic risk analysis. *Journal of Earthquake Engineering.*

25 Carreño, L., O. Cardona and A. Barbat (2007). Urban seismic risk evaluation: a holistic approach. *Natural Hazards,* vol. 40, pp.137-172.

26 Khazai B. and F. Bendimerad (2011). Risk and resilience indicators. *Earthquakes and Megacities Initiative (EMI) topical report*, vol. 565, TR-1 03.

27 Burton, C. and V. Silva (2016). Assessing integrated earthquake risk in OpenQuake with an application to mainland Portugal. *Earthquake Spectra,* vol. 32, issue 3, pp.1383-1403.

28 Silva, V. and others (2014). Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment. *Natural Hazards*, vol. 72, issue 3, pp. 1409-1427.

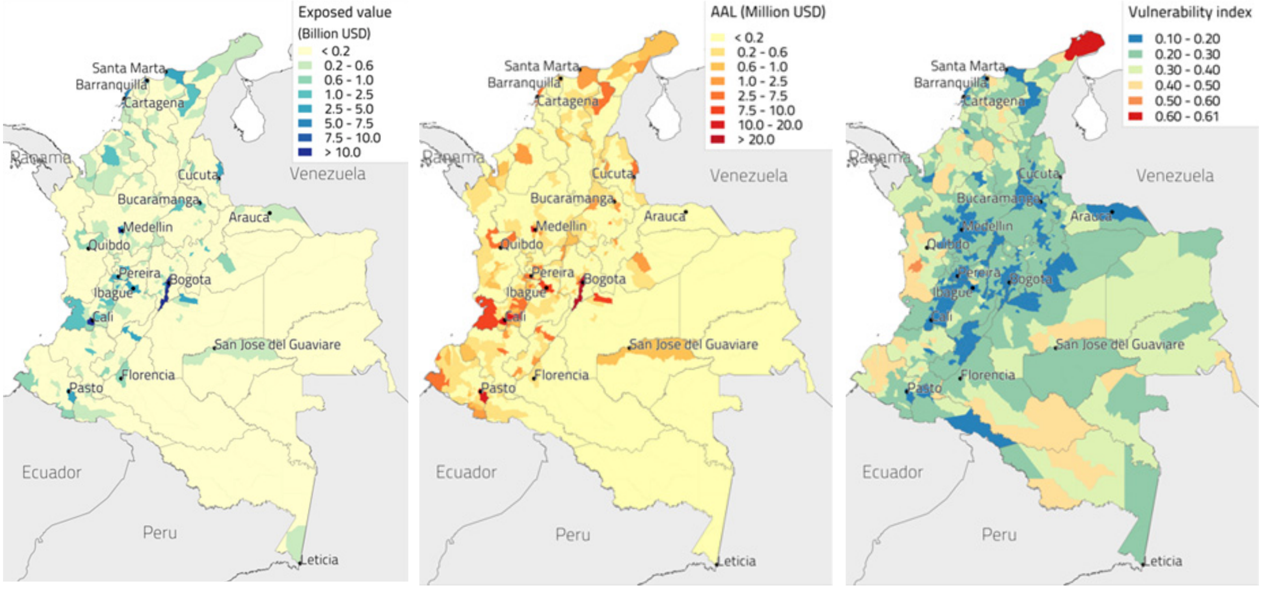

Figure 4 – Exposure model (left), average annual economic losses (centre) and socioeconomic vulnerability index (right) for the residential building stock in Colombia[28, 29]

Conclusion

Earthquakes can cause large economic and human losses, and represent a serious impediment to socioeconomic development, creation of jobs and availability of funds for poverty reduction initiatives. Earthquake hazard and risk assessment are fundamental tools for developing risk reduction measures. This process involves collecting earthquake catalogues and fault data, developing seismogenic models, selecting ground motion prediction equations, creating exposure models and deriving sets of fragility or vulnerability functions.

Combining these components for assessing earthquake hazard and risk requires complex software packages, some of which are currently publicly available. Several examples around the world have demonstrated how earthquake hazard and risk information can be used to develop risk reduction measures and ultimately mitigate the adverse effects of earthquakes.

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[29] Silva, V. and others (2014). Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment. *Natural Hazards*, vol. 72, issue 3, pp. 1409-1427.

30 Yepes-Estrada, C. and V. Silva (2017). Probabilistic seismic risk assessment of the residential building stock in South America. *Proceedings of the 16th World Conference on Earthquake Engineering*, 9-13 January 2017, Santiago.

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