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PROBABILISTIC ASSESSMENT OF EARTHQUAKE LOSSES AT DIFFERENT SCALES CONSIDERING LOST ECONOMIC PRODUCTION DUE TO PREMATURE LOSS OF LIVES

Ph.D. Thesis

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To Maria Elisa and Mario

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ABSTRACT

Seismic risk is a public risk since it is centrally produced, widely distributed, has low occurrence frequency and in most of the cases is out of control from who can be affected by it. Although there is the idea that little if anything can be done in order to reduce it in the already built environment, by means of corrective measures it is possible to decrease its levels increasing the overall seismic safety at community level.

Besides the damages and losses that can occur on the built stock as a consequence of an earthquake and the secondary losses it may pose on industrial and distribution chains, casualties both in terms of injured and fatalities need to be taken into account since those losses are to be translated into lost economic production which can alter the economic development of the affected areas and countries.

Probabilistic seismic risk models have been developed worldwide with the aim of providing information about the potential losses due to earthquakes in the areas under analysis and its estimations are usually performed in terms of direct physical damage. Anyhow, by gathering extra information about occupation levels and using damage functions that account for injuries and deaths it is possible to obtain losses in the human dimension and therefore, to integrate them within comprehensive and holistic risk assessments.

This thesis proposes a methodology to integrate the average annual losses in the human dimension with public policies by estimating in a prospective way the average annual lost economic production due to premature loss of lives which, at the same time, can be interpreted as what is to be considered the minimum public investment in corrective measures in order to increase seismic safety.

The continuous development of corrective measures in order to increase seismic safety levels is an activity that has not only gained a lot of attention but resources during the last decades mainly in developing countries. Anyhow, those investments have been closely related to the availability of resources from donors, usually multilateral development organizations and banks. Although those interventions have proven to be cost-effective by having a methodology to objectively quantify the required resources such as the one proposed in this thesis it is intended that a formal allocation of resources can take place. The methodology works at different scales so the results derived after its application can be of interest to different stake-holders and decision-makers at different levels and is applied at country level in 29 countries of Latin America and the Caribbean, in Spain, at subnational level in Colombia and at urban level in Medellín.

RESUMEN

El riesgo sísmico es considerado como un riesgo público dado que es producido centralmente, está ampliamente distribuido, tiene bajas frecuencias de ocurrencia y en la mayoría de los casos está fuera de control de quienes pueden llegar a verse afectado por este. A pesar de que existe la idea de que poco, si es que acaso algo, puede hacerse para reducirlo en lo que ya está construido, por medio de medidas correctivas es posible disminuir su nivel aumentando a su vez el nivel de seguridad sísmica de la comunidad en general.

Además de los daños y pérdidas que pueden ocurrir en la infraestructura expuesta como consecuencia de un sismo y de las pérdidas secundarias en cadenas industriales y de distribución, las personas afectadas, tanto heridas como muertas, deben ser consideradas dado que estas pérdidas se terminan traduciendo en productividad perdida que a su vez altera el desarrollo económico de las áreas o los países afectados.

Los modelos probabilistas para la evaluación de riesgo sísmico tienen el objetivo de proveer información sobre las potenciales pérdidas debido a terremotos en las áreas bajo análisis y los resultados son usualmente presentados como daños directos. A pesar de esto, mediante la consecución de información adicional relacionada con niveles de ocupación y el uso de funciones de vulnerabilidad que den cuenta de heridos y muertos es posible obtener pérdidas en la dimensión humana e integrarlas en evaluaciones integrales y holísticas de riesgo.

Esta tesis propone una metodología para la integración de las pérdidas anuales esperadas en la dimensión humana con las políticas públicas al estimar, de una manera prospectiva la producción económica promedio anual que se pierde debido a las muertes prematuras a causa de terremotos que a su vez puede ser interpretada como lo que es la inversión pública mínima en medidas correctivas para aumentar el nivel de seguridad sísmica.

El continuo desarrollo de medidas correctivas con el fin de aumentar los niveles de seguridad sísmica es una actividad que no solamente ha logrado atención sino recursos, principalmente en países en desarrollo. A pesar de ello, dichas inversiones han estado relacionadas con la disponibilidad de recursos de donantes, principalmente organizaciones para el desarrollo tanto multilaterales como bancos. Aunque dichas inversiones dan dividendos en el futuro, el hecho de contar con una metodología que permite cuantificar objetivamente los recursos requeridos para dichos fines como la propuesta en esta tesis permitiría una destinación formal de dichos recursos. La metodología puede aplicarse a diferentes escalas por lo que sus resultados pueden ser de interés para tomadores de decisiones y se aplica a nivel nacional en 29 países de América Latina y el Caribe y España, a nivel subnacional en Colombia y a nivel urbano en Medellín.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAD: Average annual deaths
AAL: Average annual loss
$AALP_{YLL}$: Average annual lost productivity due to premature mortality
AHP: Analytic hierarchy process
ART: Alternative risk transfer
CAPRA: Comprehensive approach to probabilistic risk assessment
DALY: Disability adjusted
DDI: Disaster deficit index
DRM: Disaster risk management
DRR: Disaster risk reduction
EALY: Economic adjusted life years
F: Aggravating coefficient
GAR: Global assessment report on DRR
GDP: Gross domestic product
GED: Global exposure database
GFCF: Gross fixed capital formation
GIS: Geographical information system
GMPE: Ground motion prediction equation
G-R: Gutenberg-Richter relationship
IDB: Inter-American Development Bank
LAC: Latin America and the Caribbean
LEC: Loss exceedance curve
LR: Lethality ratio
MDR: Mean damage ratio
OCDE: Organization for Economic Cooperation and Development
PGA: Peak ground acceleration
PGV: Peak ground velocity
PML: Probable maximum loss
PSHA: Probabilistic seismic hazard analysis
RT: Mean return period
R_F: Physical risk
SFDRR: Sendai Framework for Disaster Risk Reduction
SIDS: Small Island Developing States
UHS: Uniform hazard spectra
UNISDR: United Nations Office for Disaster Risk Reduction
USRi: Urban seismic risk index
YLD: Years lived with disability
YLL: Years of lost-life due to premature mortality

Chapter 1

INTRODUCTION

In this thesis a methodology to account for the impact of earthquakes in the human dimension in a prospective and probabilistic way, at different analyses scales will be developed. Although several studies have addressed the issue of casualties due to earthquakes, a further estimation of, first, the number of life-lost years due to premature mortality and, second, the earthquake's impact in terms of lost economic production contributes to a more comprehensive and wider approximation for the seismic risk modelling, management and understanding. These results serve to complement the results obtained in terms of direct physical damage by covering an additional dimension which is of importance in both developing and industrialized countries. The estimation of losses in this dimension also provide an answer to the question made by Rosenblueth (1976a) on how much a society must spend in seismic safety to protect itself against earthquakes, showing that in terms of corrective actions these are finite, even if their processes and required resources are well implemented and allocated. Seismic risk cannot be avoided but managed and the consideration of different loss dimensions contribute to the construction of a comprehensive framework for its better understanding, to raise its awareness, highlight its importance and to deliver specific outputs that can be used to mitigate it.

1.1 Motivation

The fact that the increase in population and economic development has been translated into larger exposure to natural hazards has continuously raised the loss and casualties toll for earthquakes during the past 30 years (SwissRe, 2015). This is aggravated by the following shocking figure: more than 90% of the deaths associated to natural disasters have occurred in low and middle-income countries (UNISDR, 2002; Amendola et al., 2012; Michel-Kerjan et al., 2012) despite the existence of important global efforts in the disaster risk reduction field. This of course poses both a challenge and an opportunity to further explore whether new actions derived from the development and application of new methodologies, or the way outcomes of risk assessments are communicated, are needed. Natural phenomena, where earthquakes play an important part, can damage the physical capital of any economy and the effects are reflected in a decrease of production if measured in terms of output (Auffret, 2003). Still, it is also important to account for the consequences related to the human capital dimension since, as economic development occurs, they become more important at the societal level.

The risk framework used herein combines, at the same time, possibility with reality. Possibility in this case refers to hazard given that although with today's knowledge it is possible to have an idea of what to expect, the when, where and how big regarding the next event are still unknown. Reality refers to the vulnerability (in any of its multiple dimensions) since it is tangible as of today. Additional to this combination of opposite concepts, the uncertainties associated to the results become important because a decision is expected to be made with the available results. Additionally, the concept of risk has always had an associated action (Renn, 2008) and answers regarding what to do, including the do nothing choice. With this it is clear then that those uncertainties which at first only had a scientific dimension, at some stage become philosophic as there will be an impact in society once a decision is made (Caers, 2011).

It has been stated that catastrophes can be understood as problems not yet solved of development (Albala-Bertrand, 1993) and reviewing the mortality rate in developing countries can also help to understand better this statement. Whereas seismic hazard does not depend on development, evidence shows that the death rates for earthquakes decrease with economic development and wealth (Raddatz, 2007; Raschky, 2008), and one strong reason for that is that industrialized countries have invested more in safety by, for example, developing, updating and enforcing earthquake resistant building codes, recognizing at the same time, that for them, the human capital is at least as important as the physical one (Horwich, 1997). Having said this, it is clear that seismic risk should be managed to guarantee a stable and sustainable economic environment that leads in the medium and long term to decrease and leverage the death rates between industrialized and developing countries.

The huge differences in the death tolls for the 2010 Haiti and Chile earthquakes need to serve as a reflection to acknowledge that there is no such thing as a natural disaster, but socially built processes instead, which derive in earthquakes posing significant threat to exposed populations. Negative effects are constructed socially, which requires that the measures defined for the mitigation are to be developed and applied at the same scale, also remembering that earthquakes do not kill people but buildings that collapse do. Whereas in Haiti the lack of a building code, not by negligence but because there were more urgent topics to be addressed, caused the collapse of thousands of buildings and more than 200,000 deaths, a few weeks later, an earthquake with an energy release 30 times higher happened in Chile with a death toll of approximately 500 people (even though physical damage on infrastructure was important). The case of the earthquake in Chile is a clear positive consequence of a continuous effort in the development, update and enforcement of building codes which, aside from saving lives, it also helps to protect property and wealth indirectly. According to England and Jackson (2011), most of the deaths caused by earthquakes have been the result of intraplate events with magnitudes between 7.0 and 7.5, showing that the mega-earthquakes such as the ones that occurred in Chile and Tohoku in 2010 and 2011 respectively, are not necessarily needed to reach shocking death tolls, and also that there is a saturation in vulnerability caused by the disorganized urban growth and unsustainable development which can be observed more clearly in developing countries.

Additionally, the differences between industrialized and developing countries when faced by earthquakes, do not exist only in terms of death tolls; economic losses, as a percentage of the gross domestic product (GDP), are 20 times higher in the latter (Clarke and Doherty, 2004). This is a finding that clearly tells us that improvements in earthquake safety in the human and physical dimensions are needed and that, additional to the risk identification process, the quantification of investments on seismic safety as well as their proper allocation is an issue that needs to be addressed.

Economic and demographic changes have consequences on future earthquake losses since the trend in urban population shows the increasing use of hazard prone areas by inhabitants who, either in a voluntary or mandatory way, have settled there. The decision of using a hazard prone area can be considered as voluntary in cases where occupants, even knowing that their exposure to natural hazards is high, decide to move in to it in order to gain access to better employment opportunities and conditions. But most of the inhabitants of hazard prone areas have not had the chance to choose where to live and they use not the land that they wanted but the one they had access to. This increase of population in vulnerable urban areas, when combined with construction practices without or below the standards, leads also to a dramatic increase in the fiscal exposure in the developing countries (Ghesquiere and Mahul, 2007) given that governments, aside from being large owners of assets, are the responsible entities of last resort for the affected low-income groups when a catastrophe occurs.

Among the impacts of earthquakes, mortality needs to be understood as a direct and irreversible cost where, besides estimating the expected number of deaths, it is of relevance to attempt to quantify their effect on sustainable development. This does not necessarily have to do with assigning a cost to human lives, but to estimate the one associated to lost productivity at societal level. A question of relevance at this stage is how much should a society spend in earthquake safety and a good starting point for this quantification is based on the idea of Rosenblueth (1976a) who, under an egalitarian ethical framework proposed that a "*society should be willing to spend the expected present value of the average individual's contribution to the gross national product during the rest of his life plus the per capita wealth of the nation….*". In monetary terms, different values have been proposed by Fromm (1965) and Sagan (1972) also considering risks other than seismic but, so far, a prospective estimation of the number of life-lost years due to premature mortality because of earthquakes has not been developed. This value combined with other economic indicators can provide an order of magnitude of what is to be the minimum public investment in seismic safety to be materialized in terms of corrective actions.

Among the overall category of natural disasters, the relevance of earthquakes is high as it accounts for 9% of all global events (Guha-Sapir et al., 2013), and it has a similar order of magnitude for the casualties' toll. Seismic risk is a public risk since it is centrally produced, widely distributed, has low occurrence frequency and, in the vast majority of the cases, is out of control of those who can be affected by it (May, 2001). Generally speaking, it is a topic that does not get the public's attention and the interest of the public on reducing it is limited since there is the vague and erroneous idea that very little, if anything, can be done to achieve that purpose. Seismic risk is a matter of both public and welfare interest since, in the case that an earthquake occurs, aside from the damages on buildings and infrastructure, there are also casualties (both deaths and injuries), emergency attention and reconstruction costs, interruption of businesses and services which all together can cause large societal disruptions.

Seismic risk has a lot to do with the fact that awareness and perception are evident only in places where earthquakes have occurred within one or two generations, thus keeping an active memory about it, and hence it is in these places where it is more likely to find high building code enforcement levels and good design and construction practices. Unfortunately, these same requirements tend to be very flexible in places where important and big events have not yet occurred. Regarding the quantification of physical risk, several studies have been conducted in the recent past at national, subnational and urban level (Cardona et al., 2014; Ingeniar, 2014; Salgado-Gálvez et al., 2013; 2014a; 2014b; 2014c; CIMNE and Ingeniar, 2015), where in all of the above mentioned cases, the direct economic losses have been estimated by means of probabilistic approaches and the results are expressed in terms of probabilistic risk metrics such as the loss exceedance curve, average annual loss and probable maximum loss.

Even if from the structural engineering perspective disasters are assessed in terms of the damaged buildings and infrastructure, it is important to realize that each of them also has a political dimension (Woo, 2011) and, therefore, a comprehensive and multidisciplinary approach to their understanding, with the main objective of reducing the overall negative effects, requires involving experts from the social and economic sciences, among others fields (Cardona et al., 2008a; 2008b). If the fact that deaths can have a significant impact in the long term when assessing the development of an economy (Kunreuther and Michel-Kerjan, 2013) is taken into account as well, the importance of a comprehensive disaster risk management (DRM) strategy is evident. Our short term was at some stage our parents' long term and thus following the same idea, our long term will be, at some stage, the short term of our children. In all cases, all time-horizons should be considered to have the same importance.

For a comprehensive assessment framework, the effects of earthquakes in a society should be understood both as the destruction of capital stock as well as the loss of human lives and its medium and long term consequences. Assessing only the physical losses is not enough.

The definition of the resolution level for the risk assessments does not only depend on the available data and resources but on the scope and intended use of their results. Whereas a national assessment is useful for comparison purposes and can also provide an order of magnitude of potential losses, which is information of interest to high governmental officials, high resolution urban assessments can provide data to derive concrete DRM measures such as subsidized property insurance strategies, as is the case of Manizales, Colombia (Marulanda et al., 2014), or to provide input data of interest in the urban resilience evaluations by means of holistic risk assessments (Carreño et al., 2007; 2012; Salgado-Gálvez et al., 2016a).

Independent of the hazards to be considered, DRM is a fundamental pillar to guarantee the sustainability of any system because ignoring the increasing risk makes the future panorama unaffordable (Douglas, 2014). During the past years, presenting the overall natural catastrophe losses on an annual basis has become a common practice using graphs like the one shown in Figure 1-1 (SwissRe, 2015). Although these values may contain valuable information, they can also be misleading and provide the idea that natural catastrophes are more frequent than before. Even if in absolute values it is true that the increasing trend exists, it is important to contextualize these losses over time and understand that because of social and economic development processes occurring worldwide, economic growth and wealth is translated into denser and bigger urban settlements, where nowadays urban GDP accounts for more than 80% of the total GDP (UNISDR, 2013). Demographic growth, higher population density due to limited space in urban areas, and development on coastal areas have increased both the total exposed value and its concentration, being the main cause for the increase recorded in terms of disaster risk.

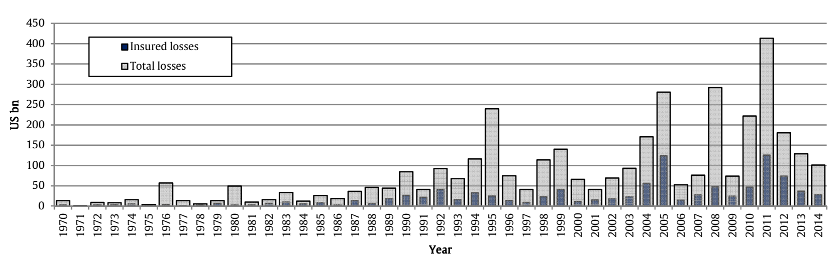


Figure 1-1 Natural catastrophes total and insured losses (1970-2014)
Source: SwissRe (2015)

On average, natural disaster losses have been quantified between U$250 and U$300 billion[1] per year (UNISDR, 2015a) and some attempts to normalize the losses by population and wealth have shown that it is more or less a constant value (AIR, 2015). Figure 1-2 shows the property premiums written over the past 35 years[2]; since these are directly related to the exposed value, the evident exponential increase portrays the fact that the increase in exposure and wealth, both in geographical extent and economic terms, has been the main cause for increasing losses, having more influence than hazard or vulnerability. Extreme events will continue occurring on large urban areas and unfortunately, for the reasons explained above, new records in terms of damages, losses and casualties are expected to be reached. With increasing rising population, worst is yet to come (Woo, 2011).

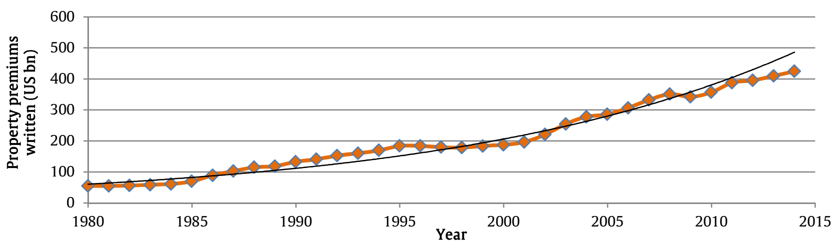


Figure 1-2 Property premiums written (1980-2014)
Source: SwissRe (2015)

Even if exposure is the main driver for the increase in the monetary value of natural disaster losses, it is important to review some aspects related to the physical vulnerability that also have contributed to the increase in the overall loss values. Economic development processes have caused some markets to grow very fast and, in order to match demand with output, countries have taken a relaxed attitude towards quality control and building code enforcement. When the quality of the construction is based only on an empirical know-how and there is a blind trust in previous experiences and common sense instead of good engineering practices, which is close in hand with the exposure, the physical vulnerability will grow.

Earthquakes also need to be understood as potential economic shocks of high relevance since more than 400 million people live in areas of high seismic hazard. Besides damage on the capital stock, deaths are also an immediate consequence that generates losses and disabilities for the poorest to recover (Guha-Sapir and Santos, 2013) and thus the combined consequences are a latent threat to human and economic development. The political stability of a country can also be jeopardized by their occurrence and this is another relevant aspect since it is directly related to competitiveness (UNISDR, 2013) and, therefore, to

[1] In this thesis 1 billion is 1,000,000,000
[2] It has been assumed that property accounts for 20% of the non-life business excluding motor.

economic development. The collapse of a building is always going to have an associated value which is much higher than just its replacement cost and even in the cases where no casualties are recorded, cleaning debris and maintaining the order in the neighboring zones is expensive and it is a cost usually born by the governments (Cohen and Noll, 1981).

In terms of fiscal vulnerability of the States, outcomes of several research studies have addressed the importance of a prospective disaster risk management strategy (Ghesquiere and Mahul, 2007; Cardona, 2009; Marulanda, 2013; Ley-Borrás and Fox, 2015). Nevertheless, it is important to remember that at governmental level it is key to quantify, beforehand, the potential impact in terms of damages, losses and casualties that extreme events, in which earthquakes are of course included, can cause. As of several years ago, the paradigm shift from assuming catastrophes as acts of bad luck to comprehensive disaster risk management has occurred, and it has also been understood that risk management is a topic that requires both intervention and political management (Renn, 2008) even if different conceptions on concepts such as who should pay or who is to be held responsible for the losses caused by natural events exist (Kleindorfer and Kunreuther, 1999). Political will and solid institutions are required for the development of comprehensive DRM schemes and sustainable initiatives since technical studies by themselves, even if they are very good, have proven to be unable to lead to concrete actions aiming to reduce risk (GFDRR, 2014). Relying on external aid after the occurrence of earthquake disasters unfortunately does not contribute to the creation of suitable economic and political institutions, both needed to fight the poverty cycle in which natural disasters have proven to play a fundamental role.

In this field, the concept of risk is always connected to a decision-making process; results of seismic hazard and risk assessments are to be used as key inputs for this process (McGuire, 2001) and, because of that, the uncertainties are important. To account for these, the use of probabilistic models is preferable where these uncertainties are included and quantified in a transparent manner. However, handling uncertainty in a transparent way does not increase nor does it improve the accuracy of the results (Bommer, 2003), but it provides a wider range of interpretation for the user of the results. Uncertainty in earthquake engineering can be classified in two main groups, the demand and in the capacity, where in the first category uncertainties related to the wave propagation, dynamic soil response, structural behavior and limit states of the systems are considered, whereas those associated to the second category have to do with the capacity of the materials, the capacity of the elements and the capacity of the systems to bear different limit states (Wen, 2004). As it will be discussed in the following chapter, catastrophe risk models provide a solid basis for prospective risk assessments and despite their assumptions and limitations they have positioned themselves as useful tools for different stakeholders and decision-makers and without them, the development of important DRM initiatives such as country risk profiles, and multi-hazard insurance pools could had not been possible.

A risk that is not perceived cannot be explicitly collateralized and probabilistic seismic risk assessments, in addition to quantifying possible future losses, play a fundamental role in the process of raising risk awareness, proving to be powerful and useful tools for risk communication. The fact that an earthquake has not happened in recent times in a city may be better understood as a matter of luck instead of a guarantee that it is a permanent seismic safe zone. There are cases where cities with very different historical seismic activities (low and high) have in the medium-long term (i.e. 475, 975 years mean return period) similar hazard levels, and others where seismic risk is higher in areas with lower historical seismicity than in other seismically active areas due to relaxed attitudes in the vulnerability side (Marulanda et al., 2013; Salgado-Gálvez et al., 2015a).

The impact of natural catastrophes in economic performance and sustainable development has also been largely studied and constitutes a very interesting case where despite the myriad of studies, no agreement among the authors and researchers yet exists about the overall consequences. Some authors propose that damages caused by earthquakes on capital and human stock generate pressure in the budget which leads to the creation and implementation of new fiscal taxes in the short term and this is to be reflected in the development in the long term (Benson and Clay, 2003); whereas others propose that the occurrence of catastrophes can decrease risk in the long-term, conditioned to a reconstruction process that follows the build back better concept, that is, the use of good engineering practices and materials with better structural performance. If the damaged and destroyed stock is replaced by new assets with lower physical vulnerability, there can be a significant decrease in the overall disaster risk which without the occurrence of an event may had been impossible to achieve (Crespo et al., 2008). Additional to this, an increase on the governmental expenditure can also be reflected in a positive perturbation of the aggregated demand (Mankiw, 2014).

Seismic hazard is something that cannot be avoided and, in realistic terms, seismic risk is something that cannot be completely eliminated. Earthquake engineering has its roots on the grounds of providing safe solutions in environments of increasing demand for safety but limited monetary resources, and this inevitably leads us to what can be the definition of an acceptable risk level and, therefore, to provide a rational answer to the question of how safe is safe enough. Even if there are discrepancies on the definition of how much risk is acceptable, we all agree that today's risk levels are unsustainable. To define how safe is safe enough, technical analyses that only focus on the physical aspect are not sufficient (Renn, 1992) and, therefore, the consideration of other dimensions and disciplines is required.

Under the guiding principle included in the Sendai Framework for Disaster Risk Reduction – SFDRR (UNISDR, 2015b) which states that each State has the primary responsibility of reducing disaster risk while at the same time managing the risk of disasters with the aim of protecting persons and property (which is also related to the human right to development), a quantitative answer based on probabilistic risk models for estimating what is to be the minimum investment on corrective measures regarding seismic safety, using the methodology proposed in this thesis attempts to contribute in this aspect by providing an order of magnitude of the average annual lost economic productivity due to premature mortality due to earthquakes and to bring into perspective an additional dimension other than the direct impact in terms of physical losses in the capital stock. Additionally to highlighting its relevance, it can also serve as a basis for establishing the monetary resources needed, in terms of public investment, for corrective measures with the goal of reducing mortality due to earthquakes. The proposed methodology can be applied at different resolution levels, an issue which provides flexibility since whereas in some cases overall figures at country level are required, detailed urban risk assessments may be more useful and relevant in other cases since it is in these areas where the largest losses are expected, additional to the different legal and administrative frameworks and scales in which budgetary decisions are made.

The topics covered and proposed in this thesis are directly related to two different priorities of the SFDRR (UNISDR, 2015b); specifically with priorities 1 (understanding disaster risk), 2 (strengthening disaster risk governance to manage disaster risk) and 3 (investing in disaster risk reduction for resilience). Regarding the latter one, it is stated that it is important to allocate the necessary resources for the development and implementation of disaster risk reduction strategies, but to do this in an appropriate manner, it is also important to quantify the needed resources in a prospective way.

1.2 Objectives and scope of this thesis

The general objective of this thesis is to develop a methodology that serves to estimate the lost economic production due to premature mortality due to earthquakes, which can also be used for the estimation on what should be the minimum public investment in seismic safety by means of corrective measures with the objective of reducing earthquake mortality. This with the aim of going beyond the estimation of deaths in terms of overall figures and showing that within a sustainable framework, the expenditure and allocation of that investment is to be executed within a finite timeframe which allows for the development of a public policy which has an end. The proposed methodology is robust enough to be applicable at different resolution levels (i.e. national, sub-national and urban) for the cases where the required data are available.

The following specific objects are also addressed in this thesis:

- To present and make use of a transparent fully probabilistic risk assessment framework.
- To balance the relevance of human capital with the physical capital in the framework of probabilistic seismic risk assessments.
- To develop a set of lethality functions associated to building collapse compatible with open-source probabilistic risk assessment software.
- To raise seismic risk awareness by considering a different loss dimension than the traditional physical stock one.
- To evaluate the pertinence and applicability of the proposed methodology at different resolution levels.
- To evaluate the pertinence and applicability of the proposed methodology in countries with different income levels.
- To show that a seismic safety public policy with finite resources can be developed with a robust estimation of what is the minimum annual investment.
- To highlight the scope, capabilities and limitations of CAT-Models using the comparison of recorded damages and losses against modelled ones for Lorca, Spain.
- To propose a metric based on investment metrics that can be integrated within the Sendai Framework for Disaster Risk Reduction (SFDRR) priorities, useful for evaluation and monitoring.

The scope of the thesis covers the prospective and probabilistic estimation of deaths due to earthquakes and its effects in terms of lost economic production. It is not intended that the results obtained, at any stage herein, are interpreted as the assignation of a value to a human life. An egalitarian approach has been chosen in the assumption that all lives have the same importance regardless age or gender allowing each of them to contribute equally to the economic production and also that the results of loss of lives due to earthquakes obtained in this thesis are to be understood as average annual values.

Several factors have been identified as drivers of earthquake lethality such as building class, response, time of the day, season, secondary hazards and construction practices. Building classes and their collapse probabilities are directly accounted for whereas and time of the day and seasonality factors are considered in an indirect way. Since only deaths caused by building collapse immediately after the earthquake are considered, the implication of the response time and capacity of the affected area is out of the scope of this thesis.

1.3 Outline of the thesis

This thesis is organized as follows: Chapter 2 presents a state-of-the-art review for several topics of interest within the proposed methodology such as CAT-

Models, seismic risk assessment frameworks, risk metrics and indexes, retrospective and prospective earthquake casualties' estimation and some ideas on the acceptable risk concept. Chapter 3 presents a review of different perspectives regarding the economic impact of earthquakes assessing what can be affected and how, the identification and selection of relevant macroeconomic metrics and how earthquake risk is related to sustainable development. Chapter 4 explores the topic of acceptable risk in earthquake engineering covering aspects such as who should make the decision followed by the development of some case-studies related to seismic hazard and seismic design coefficients where the acceptable risk is defined both implicitly and explicitly. Chapter 5 develops the proposed methodology to estimate the lost economic production due to premature loss of lives because of earthquakes exploring its scope, limitations, assumptions and data requirements. Case studies at different resolution levels and in different regions of the world are developed and the results are shown as well as a set of rankings to assess the implications of the minimum public investment on seismic safety. Chapter 6 explores the validity of the chosen methodology and tools used for the estimation of physical and human losses by comparing modelled losses with the observed ones after the May 2011 earthquake in Lorca. Finally, Chapter 7 presents the conclusions of this work as well as identifying future research lines connected to the topic.

A set of annexes present complementary information regarding different aspects of the work presented herein. Annex 1 shows the PHSA framework and methodology used in this thesis as well as the input data and results for the models used at global and national level herein. Annex 2 shows the summary of the physical and human vulnerability functions used in the different case-studies developed in this thesis. Finally, Annex 3 shows a list of publications in peer-reviews journals, books, participation in international conferences and congresses and projects related to the thesis.

Chapter 2

STATE-OF-THE-ART REVIEW

2.1 Catastrophe risk models

Seismic risk assessment is not a new subject and, whilst developed in the late 1930's, only after more than 50 years its use increased in several fields following the dissemination of the work of Cornell in 1968 (Grossi et al., 2008). Because of the characteristics of some natural hazards in terms of their low occurrence frequency and high impact characteristics, an important shift in the way losses were estimated took place after the occurrence of hurricane Andrew in 1992. This event showed that the classical actuarial approach could not account for the end tails and that uncertainties needed to be considered in an explicit and rigorous way within the models and thus, that CAT-models which already existed by then, but were not widely used in the modelling industry, were far more suitable for the development of those assessments. Even if hurricanes have different characteristics in terms of their origin, formation and propagation than earthquakes, they can also be considered as extreme events and the lessons learned with Andrew back in 1992 were quickly incorporated to other hazards. It was not long after that when the Northridge and Kobe earthquakes proved the importance of the CAT-models for the quantification of potential earthquake losses and for its use within the risk modelling industry to become a standard.

The objective of CAT-models has been, from the beginning, to provide in advance an order of magnitude for the overall potential damages, losses, injuries and deaths associated to natural hazards (Grossi et al., 2008; Guy Carpenter, 2011; Cardona et al., 2014). They are not intended to provide exact figures to be directly compared with those recorded in the aftermath of the occurrence of a real event since, when dealing with exceedance probability metrics, what can be obtained is the probability of occurrence of a certain size of losses and not the probability of a specific event to occur. The probability that the observed losses from one event are the same as the ones modelled for it are, in all cases and regardless the severity of it, very close to zero. However, comparing recorded damages and losses against those obtained with CAT-models have always provided important information and lessons which have contributed to increase their understanding and promote new developments. Chapter 6 of this thesis shows the comparison between observed and modelled damages and losses, in both physical and human dimensions, for Lorca, Spain, the city which was most affected after an earthquake in May 2011 in the Murcia Region. It was observed that the modelled losses lie within the order of magnitude of the recorded ones but without matching exact figures and with important discrepancies in the geographical location of the damages. These kind of analyses should not be interpreted as calibrations but as validations of the models, since a single event is not statistically significant for those purposes and it is to be born in mind that similarity of numerical simulation with a single observation may not be more than a mere coincidence (Woo, 2011).

The use of CAT-Models has boomed in the past 25 years mainly within the insurance and reinsurance industry, and its use has been mostly related to pricing catastrophic risks, control risk accumulation, assess options to diversify risks, calculate the required monetary reserves and to assess the capacity to bear risks by companies, insurers and reinsurers (PartnerRe, 2009; Chávez-López and Zolfaghari, 2010). CAT-Models are different from other available tools to evaluate seismic risk for a single structure since the damage calculation is generally performed for several assets at the same time and, in this case, the seismic intensities that damage the exposed elements are being generated by the same event (Bazzurro and Luco, 2007). The spatial correlation needs to be considered within the assessment since it can only be assumed to be equal to 1.0, if and only if, the elements for which the risk is being assessed have exactly the same characteristics and at the same time, the hazard intensity is equal at both locations (Lee and Kiremidjian, 2007). When ignoring this fact, there can be important variations in the final results (Weatherill et al., 2015).

It is important to know in advance the capabilities, strengths and limitations of the models to ensure that they are applied within the appropriate context. CAT-Models are powerful tools that can be very useful for the purposes they were developed for, and the misuse or misunderstanding of them should not be seen as limitations or product shortages. This became more relevant after the 2004 and 2005 North Atlantic basin hurricane season where the CAT-Models were highly criticized due to their high uncertainties and a misunderstanding of their real objective.

It can be summarized that an earthquake CAT-Model is comprised by several modules that include, at least, the following:

- Seismic hazard module
- Built stock and human exposure module
- Vulnerability module
- Loss module

In the seismic hazard module, the implementation of a probabilistic seismic hazard analysis (PSHA) framework is a common practice. It has been formalized under the use of the total probability theorem after the contributions of Rosenblueth (1964), Cornell (1968), Esteva (1970) and Merz and Cornell

(1973). The objective of any PSHA is to obtain long term predictions over the occurrence of earthquakes (Kiremidjian and Anagnos, 1988) and to do so, a regionalization of the seismic activity using seismogenetic sources is usually performed where, for each of them, the magnitude recurrence is calculated based on historical seismicity records. These, combined with ground motion prediction equations (GMPEs) that relate magnitudes and distances with intensity measures such as spectral accelerations, allow obtaining intensity exceedance rates for different intensities, as shown in Figure 2-1, from where uniform hazard spectra for different mean return periods can be obtained. Each of these plots indicate, on average, the number of earthquakes per year that exceed a given hazard intensity value. If those exceedance rates are obtained at different locations, hazard maps can also be generated. For fully probabilistic risk assessments, a required output of a PSHA is a set of stochastic events that are generated for each considered seismogenetic source and where the events are compatible with their occurrence frequencies. The complete set of events generated at each source describes the magnitude exceedance rates and thus describes in a complete manner the spatial distribution, randomness and occurrence frequency of the hazard intensities in the area of analysis, for which they are required to be mutually exclusive and collectively exhaustive. The computer program CRISIS2015 (Ordaz et al., 2015) uses the above mentioned approach and it is the tool that has been selected for the development of the different PSHA's in this thesis. A detailed explanation about the PSHA methodology used in this thesis and the CRISIS2015 software can be found in Ordaz (2000; 2004), Bernal (2014) and Salgado-Gálvez et al. (2015b).

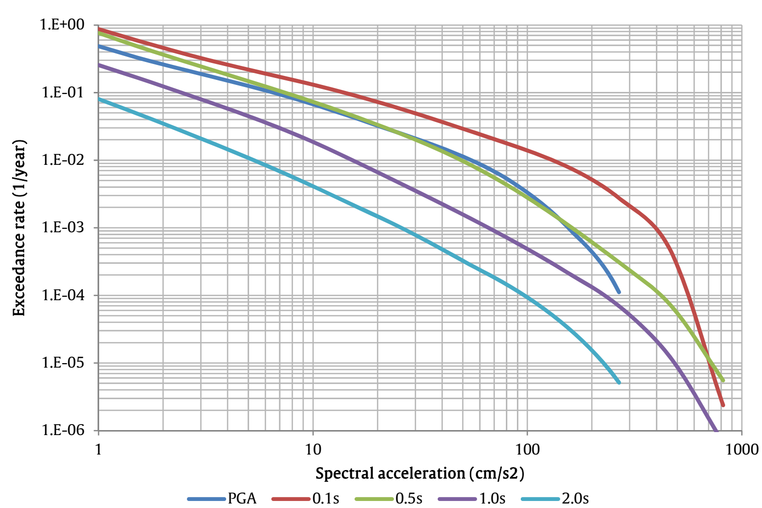


Figure 2-1 Example of hazard curves for different spectral ordinates

At urban level, considering the dynamic soil response of soft soils is relevant (Bernal, 2014). For those cases, a separate module for the definition of spectral transfer functions, such as the ones shown in Figure 2-2 for the case of Bogotá, Colombia (DPAE, 2006), which are based on geological and geotechnical information, can be used.

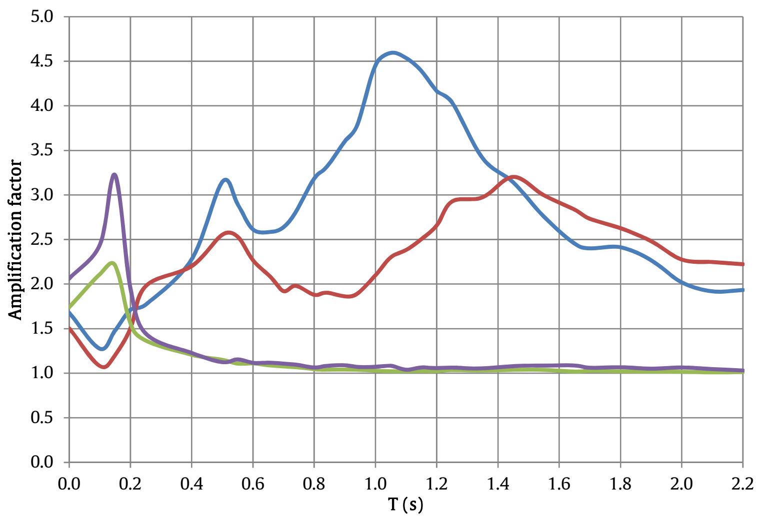


Figure 2-2 Example of different transfer functions for hard and soft soils in Bogotá, Colombia

The exposure module is used to generate databases that identify and characterize the assets susceptible to be damaged by the selected hazards (earthquakes in this case). The identification process has to do with the definition of the location and the selection of the exposed assets to be considered within the analysis, whereas the characterization process has to do with the assignation of relevant structural characteristics such as construction material, number of stories and structural systems, aside from the economic appraisal and the estimation of human occupation values. The economic appraisal is usually defined in terms of replacement costs which represent the required amount of money to repair or rebuild the damaged structure and bring it back to exactly the same original conditions. This value is generally assigned based on indexes by constructed area which typically does not coincide with the market value of the assets given that for it to match, the economy must be in an optimal condition and the market must be perfect (Hallegate and Przyluski, 2010). Since population is a dynamic parameter, different occupation scenarios based on both the use of the dwelling and the day, time and seasonal characteristics can be used. The use of a full occupation value in most cases leads to a serious overestimation of the consequences and is hardly chosen. Exposure databases can be developed at different resolution levels, ranging from coarse grain country level, as shown in

Figure 2-3 for the exposed value in urban and rural areas of Spain and Portugal using a 5x5km spatial resolution, to detailed urban level with building by building resolution, as shown in Figure 2-4 for the public and private buildings of Medellín, Colombia.

Figure 2-3 Example of coarse grain exposure database for the urban and rural areas of Spain and Portugal[3]

The vulnerability module is used for the estimation of loss functions. The first task is to identify which is the hazard intensity that better correlates with the expected damage. For the case of buildings, it has been found by Luco and Cornell (2007) that the best intensity measure is the spectral acceleration (*Sa*), but in the case of pipelines, it has been found that the best intensity measure is the peak ground velocity (*PGV*) (ALA, 2001). It has been shown that vulnerability has several dimensions (Cardona, 2001; Carreño et al., 2007) and, therefore the second task is to define which one (or ones) is to be covered by the loss functions; CAT-models mainly focus on the physical and human dimensions. Additionally, given that different approaches exist for defining and quantifying the physical vulnerability of exposed assets, such as fragility curves and damage probability matrices (Salgado-Gálvez et al., 2015b), within a fully probabilistic risk assessment framework, *vulnerability functions* are needed. These are continuous functions which relate the hazard intensity with damage and loss values by considering their expected value as well as a dispersion measure, thus accounting for a probabilistic representation which explicitly addresses the

[3]http://risk.preventionweb.net/capraviewer/main.jsp?tab=1&mapcenter=0,2965169.792775&mapzoom=1

uncertainties. A hypothetical vulnerability function is shown in Figure 2-5 where the continuous line corresponds to the mean damage ratio (*MDR*), whilst the dotted line corresponds to the standard deviation. It is important to bear in mind that these two probability moments have the same importance in the definition of the vulnerability and that no probabilistic seismic risk assessment can be performed if any of them is missing.

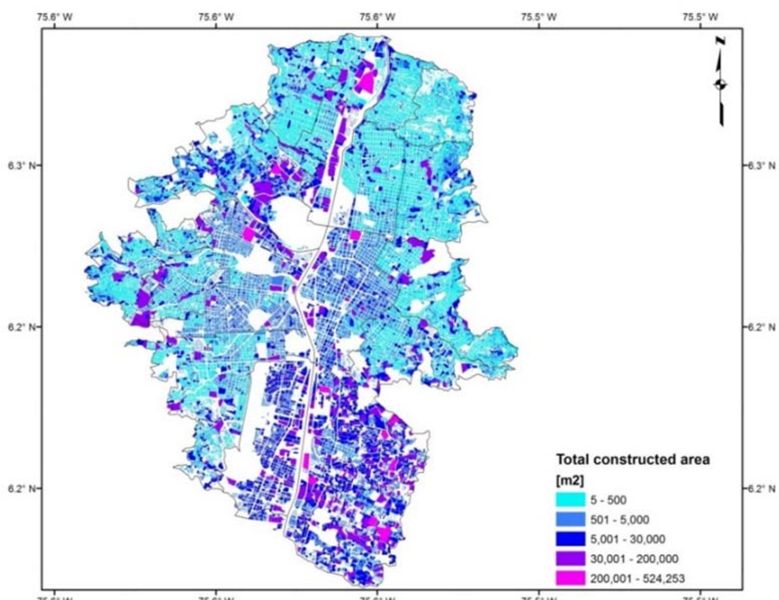


Figure 2-4 Example of detailed urban exposure database for Medellín, Colombia

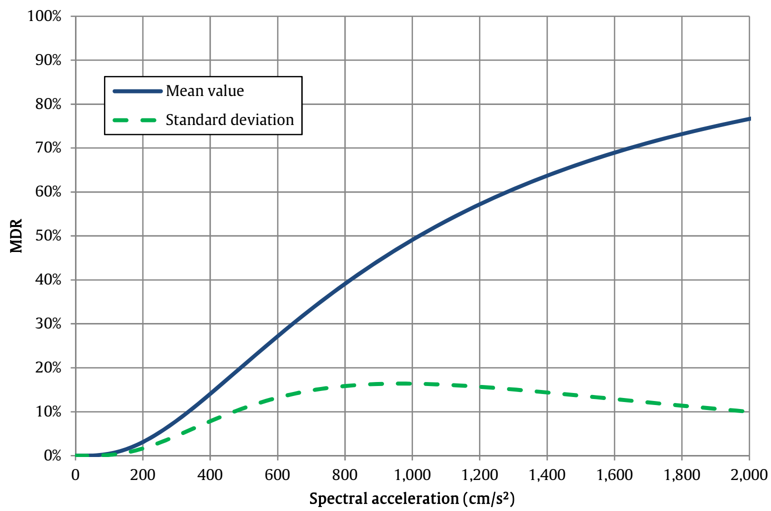


Figure 2-5 Schematic representation of a vulnerability function

Finally, the loss module is where the convolution of hazard and vulnerability occurs. When hazard is represented by means of stochastic events, the participation of every event included in the set is considered, from which the hazard intensity is then obtained for the locations of the exposed assets, which is then used to enter the vulnerability function associated to each asset, from which the *MDR*s are finally obtained. Since the economic appraisal of the elements is done using replacement costs, those *MDR* are translated into monetary units. Figure 2-6 shows the calculation flowchart of a fully probabilistic and event-based risk assessment. In summary, for every event and for each asset the damage is estimated and the probability density function of each event is obtained. Once those probability density functions are calculated for all events, the loss recurrence for different loss levels is obtained. The above mentioned modules (i.e. hazard, exposure, vulnerability and loss) show how this is a multidisciplinary field that combines engineering, geography, finance and economy among other expertise.

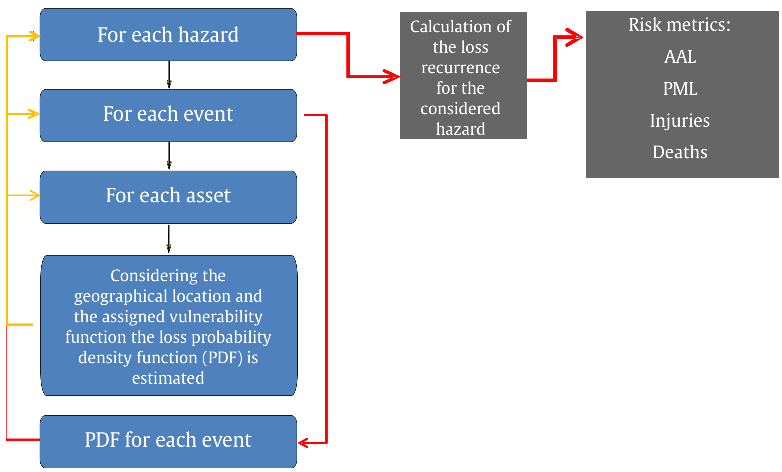


Figure 2-6 Probabilistic and event-based risk assessment flowchart

CAT-models of two types exist. The first ones are proprietary models developed by companies that mainly calculate risk considering perils of different origins (i.e. geological, hydrological, and anthropogenic) for the insurance and reinsurance industry such as Risk Management Solutions (RMS), AIR Worldwide and EQECAT. Those models are licensed tools in which the modeller, despite knowing how to use them, in some cases does not know the full details of the data contained in them (i.e. hazard and vulnerability models). Insurance and reinsurance companies also have in some cases proprietary models, developed either for business reasons or for comparison purposes with the other commercial models, and given that they are proprietary, their details are unknown to the public audience. CAT-models should not be considered at any stage as the sole element for decision-making, but as tools that provide valuable information to the people who are in charge of making decisions.

The second type of models correspond to open-source initiatives that have been promoted mostly during the past 8 years by public international development organizations like The World Bank, the Inter-American Development Bank and the United Nations International Strategy for Disaster Risk Reduction (UNISDR) with the aim of providing access to probabilistic risk assessment tools to developing countries, where the models have the same rigor as the proprietary ones but have a higher transparency in the calculation process by being open-source models. One of those initiatives is the CAPRA Platform (Cardona et al., 2012; Velásquez et al., 2014; Velásquez, 2015). Regardless of its category, nowadays understanding how these models work is more important than ever and an increasing demand for their explanation and transparency has been largely observed.

In this thesis, the CAPRA platform has been chosen for all the probabilistic seismic hazard and risk assessments. The modules shown in Figure 2-7 correspond to those used in this thesis. The CAPRA platform tools have been chosen since they are part of an open, well-known and generally accepted probabilistic risk assessment framework that has been used at international level for developing seismic hazard maps incorporated in earthquake resistant building codes (Tena-Colunga et al., 2009; Salgado-Gálvez et al., 2010; 2015c; IGN and UPM, 2013) and risk assessments ranging from detailed urban studies (Marulanda et al., 2013; Salgado-Gálvez et al., 2014) to coarse grain global ones (Cardona et al., 2014; CIMNE and Ingeniar, 2015) using the same consistent methodology and deriving results in terms of probabilistic risk metrics explained in detail on section 2.3 of this thesis. Concretely, for the seismic hazard assessment, this thesis used the computer program CRISIS 2015 (Ordaz et al., 2015), whereas for the probabilistic loss assessment (both physical and human) the CAPRA Team RC+ software was selected. The latter corresponds to an improved and parallelized version of the original CAPRA-GIS (ERN-AL, 2011).

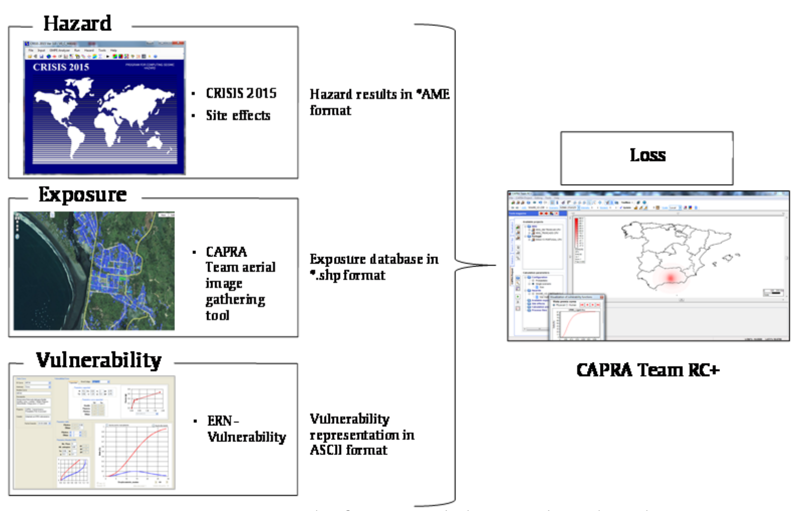


Figure 2-7 CAPRA platform modules used in this thesis

Not only the probabilistic models are important but also how the obtained results are used for decision-making purposes (Cardona, 2001). In the case of CAT-models, the results are of interest for different stakeholders and decision-makers, for example:

- *Owners* of a considerable large number of elements (e.g. Governments) since they provide a solid conceptual framework which is useful to assess different elements related to financial instruments and sovereign risk in the light of quantifying consequences of uncertain events (Ley-Borrás and Fox, 2015).
- *National and city governments* willing to know the potential losses as well as the capacity of emergency services and teams.

- *Insurance and reinsurance companies* to define exposure concentration and maximum loss levels as well to develop pricing processes.
- *Development planners at national level* willing to account for the cost of contingent liabilities because of natural disasters.
- *Institutions that lend money* for a varying range of purposes, from traditional real estate mortgages to reconstruction activities.
- *Academics* involved in the development of methodologies related to any of the stages of probabilistic risk assessments.

Uncertainties are implicitly accounted for when dealing with probabilistic tools, but recently the interest on knowing how some of the uncertainty aspects are considered and what their influences in the final results are, has increased. Uncertainties are inherent despite the scale of the analysis due to lack of data (Caers, 2011) but their existence does not make the model wrong or unsuitable as long as they are acknowledged. Because many of the uncertainties in the seismic hazard and risk assessment context can take long timeframes to be reduced, today's objective is to be as transparent as possible with the their handling.

Uncertainties also exist due to measurement errors and mistakes when processing the raw data, because even if data have been gathered in a careful way, its resolution may be coarse compared to the resolution level of the model (Caers, 2011); additionally, errors in the interpretation of the base data and final results is another common source for it (Chávez-López and Zofaghari, 2010). Uncertainties can also influence the way in which models are used since it can be an excuse for the selection of those that produce the results a stakeholder is expecting and is comfortable with despite their validity (Calder et al., 2012), or to take advantage of its existence and use it as a reason to keep reserves lower than required in the case of insurance companies (Bohn and Hall, 1999).

Uncertainties have been a topic of large research within the CAT-models field but, up to now, a formal definition to assign their importance or to create rankings according to their relevance does not exist. Currently, a process known as model blending has been suggested by rating agencies such as Standards and Poor's and A.M. Best, to properly use the results from different models in which the best of every model is used to produce an enhanced result with the aim of increasing transparency in the market and promote their openness and interoperability. Still, the blending of two poor models of course cannot produce a good result (Calder et al., 2012).

Uncertainties are generally classified in two broad categories: aleatory and epistemic. The first ones are related to the random characteristics of an event and, therefore, the fact that it cannot be reduced is acknowledged beforehand. The second category corresponds to those associated to an incomplete understanding of the phenomena under study but that with a larger set of observations can be reduced. Although in theory, epistemic uncertainty is always on the decrease (Murphy et al., 2011), the aleatory uncertainty can still be better identified, even if not reduced (Woo, 2011). Quantifying uncertainty, although desired, is a very challenging task where, unfortunately, it cannot be estimated by subtracting what one does not know from what one do knows (Caers, 2011). Still, in classic PSHA when the nature of uncertainties is considered in an incorrect manner, there may not be differences in the expected values but the variances will differ (Ordaz and Arroyo, 2016).

Unfortunately, there is still the belief that CAT-models completely eliminate uncertainty when in reality they perform a rational consideration and propagation of uncertainties, and this causes the results to be interpreted as accurate figures ignoring the fact that decisions must be made by considering the error ranges as well as the expected value (Grossi et al., 2008). What is to be considered uncertain and to which category it belongs to is a matter that depends on the context (Der Kiureghian and Dotlevsen, 2009). That decision can neither be fixed in time nor in space and, moreover, defining which uncertainties are aleatory, may result in a philosophical debate. Nevertheless, that identification and classification process represents a challenge and the decision is to be made by the modeller (Murphy et al., 2011).

Typical results of a probabilistic risk assessment are in the form of annual exceedance probability curves like the one shown in Figure 2-8. First, an observation timeframe is selected (usually set in one year) and the exceedance probability for several loss values is estimated. The plot is always decreasing since the larger the loss the lower its exceedance probability, but when reading these graphics it is always useful to bear in mind that there are uncertainties regarding the frequency and severity of the considered events. There can always be a large variation in the exceedance probability given a loss value and a large variation in the loss given an exceedance probability. In all cases, it is important to remember that within a probabilistic risk assessment framework such as the used herein, the random variable corresponds to the loss and not to the exceedance probabilities or rates. As with any other models, CAT-models are idealized and abstract representations of reality where even though they are based on complicated equations and probability distributions, a lot of assumptions are made. No CAT-model can ever be better than the underlying data it uses, and regardless how state-of-the-art it is, the garbage in-garbage out principle applies (Grossi et al., 2008).

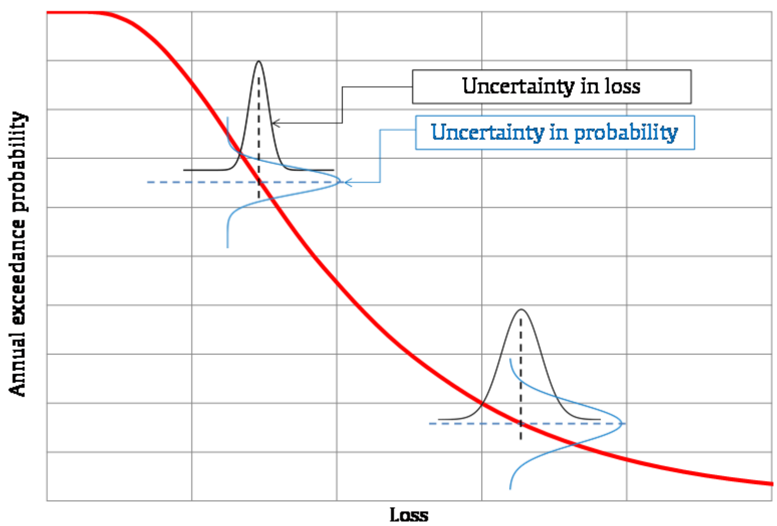


Figure 2-8 Example of an annual exceedance probability curve

The use of annual exceedance probability curves instead of loss exceedance curves, which relate loss amounts with their associated annual exceedance rates, has been recommended recently since the concept of mean return period is still misunderstood and risk results are better communicated in terms of exceedance probabilities rather than mean return periods (Serinaldi, 2014). Cat-models are still to be better integrated into DRM since they are useful tools for obtaining results which can be then be used in any of the four main components (Cardona, 2009). These components cover diverse topics such as risk transfer strategies (an activity that is of interest to the grantor and the taker only if the price associated to that activity is reasonable for both parties (Arrow, 1996)) and the development of benefit/cost analyses to assess the potential savings in losses due to structural retrofitting (Smyth et al., 2004; Ordaz et al., 2010).

2.2 Seismic risk assessment frameworks

Seismic risk assessments can be classified in two broad categories: deterministic and probabilistic (McGuire, 2001; 2004). The first is mostly used to assess the risk of a single exposed asset which is usually a critical facility (e.g. nuclear plants and water dams) and, for that purpose, a single event is generally used for the hazard estimation and its selection is based on the definition of a maximum credible event (MCE) described by its magnitude, depth and location. This approach is used for the estimation of worse case scenarios and is of great importance in the structural reliability field. The second category groups the assessments that take into account the existing uncertainties in the different inputs of a risk assessment (i.e. hazard and vulnerability) by not only identifying and quantifying them but by propagating them throughout the whole assessment process. These types of assessments are generally used for the estimation of losses in several assets at the same time by considering the participation of all plausible earthquakes in the region under analysis. There is also a semi-deterministic approach where, selecting one event out of the stochastic set, the damages and losses are calculated in a probabilistic way but the occurrence is set as deterministic; this approach has been developed, for example, for Medellín, Colombia (Salgado-Gálvez et al., 2016a).

According to the analytical procedure proposed by Ordaz (2000) and implemented in the CAPRA platform (Cardona et al., 2012; Marulanda et al., 2013; Velásquez et al., 2014; Velásquez, 2015), the probability density function for the loss on the j^{th} exposed asset (l_j), conditional to the occurrence of the i^{th} event is $f(l_j/Event_i)$.

Because it is not possible to calculate this probability distribution in a direct way, it is obtained by chaining two separate conditional probability distributions, the first one related to the vulnerability, that is, the expected loss given a hazard intensity level (Sa), and the second one to the hazard, that is, the hazard intensity level (Sa) given the occurrence of the i^{th} event.

$$f(l_j \mid Event_i) = \int_0^\infty f(l_j \mid Sa) \cdot f(Sa \mid Event_i) dSa \tag{2.1}$$

The probability density function of the loss for the i^{th} event is computed by aggregating losses from each individual exposed asset. Since loss is computed as a random variable, it requires to be aggregated in a probabilistic way. The following expressions are used to calculate the expected value of the loss, $E(l/Event_i)$, and its corresponding variance, $\sigma^2(l/Event_i)$ for each event:

$$E(l \mid Event_i) = \sum_{j=1}^{NE} E(l_j) \tag{2.2}$$

$$\sigma^2(l \mid Event_i) = \sum_{j=1}^{NE} \sigma^2(l_j) + 2 \sum_{\substack{k=1 \\ k<j}}^{NE-1} \sum_{j=2}^{NE} \text{cov}\left(l_k, l_j\right) \tag{2.3}$$

where NE is the total number of exposed assets, $E(p_j)$ is the expected value of the loss at the j^{th} exposed element given the occurrence of the i^{th} event, $\sigma^2(l_j)$ is the variance of the loss at the j^{th} exposed element given the occurrence of the i^{th} event, and $\text{cov}(l_k,l_j)$ is the covariance of the loss of two different exposed elements. The covariance is calculated using a correlation coefficient $\rho_{k,j}$ set equal to 0.3 and taking into account the standard deviations for losses in different assets

$$\sigma^2(l \mid Event_i) = \sum_{j=1}^{NE} \sigma^2(l_j) + 2\sum_{\substack{k=1 \\ k<j}}^{NE-1} \sum_{j=2}^{NE} \rho_{k,j}\sigma(l_k)\sigma(l_j) \quad (2.4)$$

Seismic risk is better expressed in terms of loss exceedance rates, which specify the frequencies or probabilities with which events that reach or exceed a specified value of loss will occur. This annual loss frequency expressed in terms of an exceedance rate, can be calculated using the following equation, which is one of the many ways adopted by the total probability theorem:

$$v(l) = \sum_{i=1}^{N} \Pr(L > l \mid Event_{\text{i}}) \cdot F_A(Event_{\text{i}}) \quad (2.5)$$

where $v(l)$ is the exceedance rate of the loss l, $\Pr(L>l|Event\ \text{i})$ is the probability that the loss is larger than l given the occurrence of the i^{th} event and $F_A(Event\,\text{i})$ is the frequency of occurrence (in annual terms) of the i^{th} event. In this equation the sum is performed for all the scenarios included in the stochastic set that produce any loss level on the exposed assets. The loss exceedance curve contains all the necessary information to describe, in probabilistic terms, the process of occurrence of events that generate losses. With the tools used in this thesis, the exceedance rate is calculated for 50 different loss levels, logarithmically spaced between zero and a value equal to 80% of the total exposed value. Larger losses than said value are not likely to occur and, therefore, are not considered.

To convert results from *LEC* to exceedance probabilities over a given timeframe, the following expression can be used.

$$\Pr(L > l)_t = 1 - e^{-v(l)\cdot t} \quad (2.6)$$

where $\Pr(L>l)_t$ is the loss probability exceedance over the timeframe t (expressed in years) and $v(l)$ is the exceedance rate of the loss l. It is also important to bear in mind that for the estimation of the annual probability of exceedance what is used is the mean exceedance rate and not the number of earthquakes per year since the last is considered as a random variable that does not have an associated known value for any given year (Ordaz and Arroyo, 2016).

Once the convolution process between the hazard and vulnerability is performed, the expected loss information is obtained for the whole exposure database. These results include the consideration of the complete set of stochastic events (representing all the small, moderate and big plausible events), the amplification provided by the soil conditions through the transfer functions (if included) and, finally, the vulnerability functions that will lead to the expected losses in each exposed element.

The loss l that is calculated with Equation 2.5 is the sum of the losses that occur in all the exposed assets and, because of that, it is worth highlighting the following:

- Loss l is an unknown quantity and its value, given the occurrence of any scenario, cannot be quantified with any degree of precision. Because of that, it is assumed to be a random variable and its probability distribution, conditioned to the occurrence of an event with certain characteristics, must be calculated.
- Loss l is calculated as the sum of the losses, considering all the stochastic events that generate any damage level and occurring on each of the exposed assets. All the values in the sum are random variables and it is evident that there is certain degree of correlation among them; therefore, this aspect should be included in the analysis.

The probabilistic seismic risk assessment methodology based on Equation 2.5 and explained in the block scheme of Figure 2-6, can then be summarized in the following steps:

1. For each event, the loss probability distribution for each of the assets included in the exposure database is determined.
2. From the loss probability distribution of each asset, the probability distribution of the sum of those losses is calculated, taking into account the correlation that exists among them.
3. Once the probability distribution of the sum of the losses is calculated, it is necessary to estimate the probability that it exceeds any arbitrarily selected loss value l.
4. That probability, multiplied by the frequency of occurrence (expressed in annual terms) of the event, is the contribution of it to the loss exceedance rate.

These four steps are repeated for all the events included in the stochastic set and, then, Equation 2.5 provides the loss exceedance rates $\nu(l)$.

2.3 Risk metrics and indexes

This section presents the most relevant probabilistic risk metrics as well as some of the seismic risk indexes that can be obtained and/or derived from probabilistic CAT-models. It is important to clarify that the biggest contribution of the metrics to DRM is that they serve as quantifiable values for the risk to be dimensioned, managed and monitored. Although in some cases it has been argued that describing and communicating risk by means of a unique number causes a great loss of information (Artzner, 2000), the mentioned metrics and indexes contributed essentially to the risk communication and risk understanding process. Among the existing risk metrics the more relevant are:

- The *Average Annual Loss* (*AAL*), or expected annual loss, is the expected loss value normalized in annual terms. First proposed by Freeman (1932) using an actuarial approach, it has become a widely used metric for ranking and comparison purposes. It is a relevant value given that if it is assumed that the occurrence frequency of damaging events is stationary, the accumulated losses in a long enough timeframe would equal the summed *AAL* value. In a simple insurance system, the *AAL* is equivalent to the annual premium. *AAL* can be calculated by integrating $v(l)$ given by Equation 2.5 or by using the following alternative expression:

$$AAL = \sum_{i=1}^{Event} E(L|Event\ \mathrm{i}) \cdot F_A(Event\ \mathrm{i}) \tag{2.7}$$

  It can be seen that either from Equations 2.5 or 2.8, the *AAL* is calculated considering the participation of all the hazard events by multiplying their expected loss, $E(L/Event_{\,i})$, by their frequencies of occurrence (F_A)

  Some important assumptions when calculating the *AAL* are that the exposure characteristics are constant over time and that damaged structures are repaired, considering that they are returned back to their original initial conditions immediately after the event. Since it is based on expected values, the *AAL* is relatively insensitive to uncertainty (Marulanda, 2013), and because it is a loss measure that accounts both for the severity and the frequency of all possible hazardous events, it provides a long term overview of the risk level of the analysed elements. Under the proposal of Arrow and Lind (1970), this value corresponds to the annual addition to budget for disaster response strategies. When normalized by the total exposed value, the result is known as the pure premium or burn cost. Since the *AAL* is estimated by averaging the losses, the contribution of multiple hazards can be aggregated arithmetically, which makes it very useful in a multi-hazard risk assessment framework.
- The *Probable Maximum Loss* (*PML*) is a value associated to a loss that does not occur very often and it is therefore related to long mean return periods (or, similarly, low exceedance rates). Originally proposed by Steinbrugge (1982) *PML* was introduced to establish a limit to the losses within the insurance industry, with the following subjective definition: "It should be the largest possible loss which is estimated may occur in regard to a particular risk, given the worst combination of circumstances" (Woo, 2011). There are no standards to select the mean return periods of interest, which depends mostly on the risk aversion of

the person who is doing the assessment or of the owner of the exposed assets. For seismic risk it is common practice in the insurance industry to use mean return periods ranging between 250 and 2,500 years. It was first associated to a mean return period of 475 years, similar to the one suggested by the National Disaster Coalition (Krovvidi, 2004) but, at a later time and with the objective of considering earthquakes occurring in central and eastern USA which are less frequent if compared to the ones expected in California, a 2,475 years mean return period of the seismic hazard was set. The fact that no standard exists for the mean return period selection should not be a problem since the *LEC* considers all the possibilities. Basically, it can be said that the *LEC* has an infinite set of decisions for the users, modellers and decision-makers and, thus the issue of which mean return period to select is arbitrary and will depend on their criteria. Since *PML* is directly obtained from the *LEC*, it is worth noting that the mean return periods are calculated using the total probability theorem, which means that for any loss level its exceedance rate is calculated as the sum of all the events with probability of exceeding said loss level multiplied by their probability of occurrence.

When interpreting *PML* values, a common question that arises is if the loss associated to a selected mean return period is caused by a unique event. The answer to it depends on the hazard environment. A city may be exposed to earthquakes associated to a unique seismogenetic source where it is possible to identify the event that can cause a certain loss level. On the other hand, there are cases where the events that may cause damages are associated to different seismogenetic sources and the identification process is more difficult since different events can lead to similar loss values. *PML* is also useful to assess the risk reduction obtained by diversification since it has a sub-additive property where *PML*(A+B) is always lower than *PML*(A) + *PML*(B) (Powers, 2012).

Recently it has been proposed to include specific risk metrics in the financial aspects and management of public and private enterprises by stating that their stock price should also reflect their risk values. An example of this is a proposal made by Douglas (2014) where the *PML* for 100 years should be used to assess the solvency in case of an extreme event, the *PML* for 20 years should be used to see the profit risk/earning of a company for any given year, and that different ratios can be calculated among the risk metrics (*AAL* and *PML*) and other business figures such as annual income and annual earnings, among others.

Beside the risk metrics obtained directly from the probabilistic risk assessments, a set of indexes which make use of their results has been defined for different purposes. A brief description of the most relevant ones in prospective risk management, with emphasis in the estimation of fiscal deficit and the assessment of urban resilience are presented next.

- The disaster deficit index (*DDI*) is one of the risk indices developed under the framework of the Inter-American Development Bank (IDB) indicators program (IDEA, 2005) for disaster risk management. This index measures the economic loss that a country can face in the case a natural catastrophe occurs, considering the implications in terms of monetary resources needed to cope with the situation. Hazard is considered by means of a maximum considered events (generally for 50, 100 and 500 years mean return period) and their consequences are estimated in a probabilistic way. These losses are then compared with available funding to address the situation such as insurance, reinsurance, aids, donations, disaster reserves, new taxes, internal and external credits. A *DDI* higher than 1.0 reflects the country's inability to cope with the considered extreme events even if the government gets into as much debt as possible. The *DDI* is usually estimated at country level and has been estimated for more than 20 countries in Latin America and the Caribbean.
- The urban seismic risk index (*USRi*) proposed and modified by Carreño et al. (2007; 2012) accounts for the physical risk as well as aggravating conditions which are consequence of social fragility and lack of resilience. First, a set of descriptors that capture the direct impact, such as *AAL* and casualties, are obtained and are later combined with an aggravating factor that is comprised of a set of descriptors that capture social fragility and lack of resilience issues such as violent death rates, available public space and available hospital beds. The *USRi* results are useful to identify which are the main drivers of the total risk thus providing stake-holders and decision-makers with useful information for the derivation, planning and execution of concrete actions in different fields ranging from structural engineering to urban planning to mitigate risk. This index shares some similarities with the Prevalent Vulnerability Index (*PVI*) which is also part of the set of risk indices of the IDB. *USRi* is described with more detail in Annex 3 of this thesis complemented with an application in Medellín, Colombia.
- The Risk index (*RI*) proposed by Niño et al. (2015) allows for the identification of the areas which can be affected by the occurrence of natural hazards based on the *AAL*. The *RI* is applicable at different resolution levels (from individual buildings to national proxy exposure databases) and allows for the incorporation of the physical risk results into the decision-making process, and it also helps to prioritize the use of economic resources in future investments. Since the *RI* is based on the *AAL* which is a metric that can be estimated for hazards of different origins, it can be applied within a multi-hazard context.

2.4 Earthquake casualties assessment

Aside from the physical aspect, another important dimension of seismic vulnerability and loss assessments is the human one. Over the past 20 years, efforts have been made worldwide in this field with the aim of deriving relationships to establish the expected number of casualties, both death and injured, produced by earthquakes in order to allow prospective estimations useful for the design of emergency plans. This has been a challenging effort since first of all, it heavily relies on historical data which is scarce, and second, the geographical variability of casualties is very large, even when dealing with events of similar characteristics in terms of magnitude and focal depth (Coburn et al., 1987). Human vulnerability functions are developed in terms of lethality ratios which are defined as the ratio of the number of people killed to the number of inhabitants at each considered building class at the moment of the earthquake. These functions depend on the number of stories, structural system and main construction material among the most important characteristics and have been established mainly on an empirical basis after careful examination of data from post-earthquake surveys. This issue highlights the importance of the development of global earthquake consequences databases like the GEMECD (So et al., 2012; So, 2014).

More than 90% of deaths are caused by building collapse (Coburn and Spence, 2002) if the deaths associated to secondary events such as tsunami and landslides are excluded; therefore, the focus of the assessment has been set to this specific damage state. The quantification of lost lives starts by first estimating the collapse probabilities for the different building classes that better describe the characteristics of the assets included in the exposure database, followed by the assignation of the lethality ratios associated to each of them. For the latter, a great effort for the derivation of regionally and globally applicable lethality and injured ratios has been made by different authors (Fulford et al., 2002; FEMA, 2003; Spence, 2007; Jaiswal et al., 2011; So and Pomonis, 2012; Wu et al., 2015). These functions can be integrated within the probabilistic risk assessment frameworks explained previously and by following exactly the same methodology, they can provide risk results in terms of the same metrics but now considering the human loss dimension. That is, instead of monetary losses, expected deaths and injuries are obtained.

The pioneering work of Spence and Coburn (1992) led to the establishment of human loss functions and lethality ratios that have been used for the prospective estimation of deaths due to earthquakes. As in the case of the physical vulnerability functions, it is important to select an adequate parameter to describe the hazard intensity, and different ones have been used in this field. Some parameters have been developed as a function of the event magnitude (Samardjieva and Badal, 2002; Nichols and Beavers 2003), but this has the problem that it is a measure that only accounts for the size of the event (in terms of released energy) and not for the geographical distribution of the hazard intensity. To account for the latter, macroseismic intensities like the Mercalli Modified Intensity (MMI) have been chosen by Spence and Coburn (1992; 2002), HAZUS (FEMA, 2003), Jaiswal et al. (2009) and Wu et al. (2015) for the casualties assessment.

However, it is important to bear in mind that state-of-the-art seismic hazard models make use of objective intensity measures such as spectral accelerations (*Sa*) and that even if there are empirical relationships to convert *Sa* to MMI (Worden et al., 2012), it is desirable to define the loss functions in terms of an instrumental intensity measure. Moving from an instrumental measure to a macroseismic one is considered a step backwards with todays' knowledge on the topic. In this thesis, a procedure to develop death functions starting from physical vulnerability functions using *Sa* as the hazard intensity measure is developed in Chapter 5.

The HAZUS methodology (FEMA, 2003) considers earthquake casualties as direct social losses assuming a direct relationship between structural and non-structural damage with the number and severity of casualties. This methodology has been developed for specific use within the USA but the lethality ratios have been used widely around the world given the lack of data at other locations. Only casualties caused directly by earthquakes are accounted for, and heart attacks, tsunami, fires, and landslides among others are excluded. Injuries are classified into 4 severity categories following the proposal of Durkin and Thiel (1991), and three different time scenarios are considered: 2:00am, 2:00pm and 5:00pm given that the population is differently distributed in buildings of different use (such as residential, industrial and commercial) depending on the time of day. Both indoor and outdoor casualties can be estimated using these lethality ratios and its use is mostly based on a single-scenario following an event-tree approach.

The first global effort to account in a comprehensive way for the assessment of earthquake casualties was developed by the United States Geological Survey (USGS) as the Prompt Assessment of Global Earthquakes for Response (PAGER) in 2007 with the objective of estimating, within a 30 minute timeframe, the damages, losses and casualties of every earthquake anywhere in the world. The casualty loss model is based on empirical and semi-empirical functions calibrated in terms of casualty rates using country-specific historical earthquake loss data (which means that the calibration has not been possible to be developed at a worldwide level). For the casualties' estimation, hazard is quantified by means of a shakemap with a 1x1km spatial resolution and the ground motion is quantified in terms of different parameters, ranging from macroseismic to instrumental intensities (Wald and Allen, 2007). Additionally, an exposure database that uses data from the LandScan gridded population (Bhaduri et al., 2002), demographic data from the UN Population Division and the CIA fact book, complemented with a building inventory database from the World Housing Encyclopedia, is used.

The empirical model developed by Jaiswal et al. (2009) uses historical casualty data as a function of shaking intensity. Fatality rates, v, are considered as a function of the hazard intensity (S) which can be defined by the following lognormal distribution:

$$v(S) = \Phi\left[\frac{1}{\beta}\ln\left(\frac{S}{\theta}\right)\right] \quad (2.8)$$

where Φ is the standard normal cumulative distribution function and θ and β are two free parameters of the lognormal cumulative distribution function. A country-specific model is derived in terms of estimated deaths as a function of MMI.

The semi-empirical model is defined in terms of the collapse probability of a building class as a function of the hazard intensity, expressed again in terms of MMI, and the estimated fatalities are denoted as $E(L)$.

$$E(L) = \sum_{i}^{n}\sum_{j}^{m} P_i \cdot f_{ij} \cdot CR_j(S_i) \cdot FR_j \quad (2.9)$$

where n is the number of grid cells, m the number of building classes, S_i is the shaking intensity at each location, P_i the total population at grid i, f_{ij} the fraction population at location i in building class j and FR_j is the fatality rate given collapse for building class j which can be found in Jaiswal et al. (2011).

Collapse fragility functions are defined in terms of shaking intensity, S (expressed in terms of MMI) as

$$CR_j(S) = A_j \times 10^{\left(B_j / S - C_j\right)} \quad (2.10)$$

where parameters A_j, B_j and C_j depend on the building class and can be found in Jaiswal et al. (2011).

Within the framework of the LESSLOSS project (Spence, 2007), funded by the European Commission, the 7th report accounts for the earthquake disaster scenario predictions and loss modelling for urban areas. In this report a GIS tool using state-of-the-art loss modelling software was created with the objective of contributing to seismic risk mitigation policies in Europe. Three cities in Turkey, Portugal and Greece were selected and, for each one of them, losses in terms of building damage levels and human casualties (both injuries and deaths) were quantified using the same base methodology. Human losses were derived after a classification by injury type, considering casualty severities based on the Association for the Advancement of Automotive Medicine (AAAM) injury dictionary. Death assessment considers the population per building, the occupancy at the time of the earthquake, the number of occupants trapped after the building collapse, the mortality at collapse and the post-collapse mortality. In

LESSLOSS, the injury distribution was estimated for different building classes considering the following categories: uninjured, slight injuries, moderate injuries, serious injuries, critical injuries and deaths for buildings that are completely damaged. Casualty results are obtained as an overall figure associated to single earthquake scenarios.

The World Agency of Planetary Monitoring and Earthquake Risk Reduction (WAPMERR) has developed an open tool to estimate building damages and human losses at a global scale. The hazard module quantifies hazard in terms of macroseismic and instrumental intensities and for some urban areas local soil amplification factors are available. The exposure database is comprised by a building stock distribution based on inventories that have been compiled either by engineers or by using proxies. The casualties' assessment is based on the model proposed by Stojanovski and Dong (1994) making use of collapse models compatible with the EMS-98 vulnerability classes (Grüntal, 1998) and by using the casualty matrices developed by Trendafiloski et al. (2009) which use the lethality ratios proposed in HAZUS (FEMA, 2003).

In the Global Disaster Alert and Coordination System (GDACS) framework, the casualties' assessment is based on an automatic and real-time GIS-based consequence methodology. The system, based on the location of the earthquake, estimates the number of inhabitants affected based on density data for different radii ranging from 1 to 200 km (De Groeve, 2006).

However, in most cases the scope of the assessments has been either to determine the expected overall death figure after the occurrence of one event to be used for the development of urban emergency plans, or to estimate the average annual deaths at different resolution levels by considering the participation of different possible earthquakes (Marulanda et al., 2013; Silva et al., 2014; Salgado-Gálvez et al., 2015a; 2016b), or to estimate injury types which are of interest for healthcare planners (Shoaf and Seligson, 2011).

2.5 Lost economic production due to loss of lives

Even if it is complicated due to the moral implications, the issue of quantifying the monetary impact of lost lives due to earthquakes is not new. For example, Esteva (1970) when assessing the cost of building collapse found that when this happens, the cost is 10 times higher than that of the reconstruction due to the loss of lives. More recently, in the framework of a benefit/cost analysis in Istambul, Linnerooth-Bayer and Mechler (2009) used a value of USD 1 million per life lost. Again, the objective of this thesis is not to assign or quantify the cost of a life, but the lost economic production due to premature deaths, in order to assess the lost contribution of the dead individuals to society.

Previous studies have also addressed the topic of lost productivity years, number of life-lost years and overall lost production (Fromm, 1965) using retrospective approaches for tsunami (Krishnamoorthy et al., 2005) and earthquakes (Wang et al., 2008). For the case of tsunami, using the December

2004 Sumatra event deaths statistics, a sub-national estimation of *YLL* was proposed in India and, based on the working age group and minimum wage figures, the lost productivity for one month was calculated. For the case of earthquakes, using the statistics of the 2008 Wenchuan event, the effect of injuries in public health in China in terms not only of death causes but lost of potential productive years has been highlighted. Finally, a non-monetary metric to account for the direct impact of natural disasters with different origins was introduced by Noy (2014; 2015) and applied at global level based also in disaster databases. Although the estimation of the impact in this dimension is very useful, it is also known that for catastrophic events the scarce historical data are not enough to have a complete overview of the problem and, therefore, prospective and probabilistic approaches, such as the proposed herein, are required.

In the earthquake engineering field, metrics based on *DALYs* have been proposed, such as the Economic Adjusted Life Years - EALY (Scawthorn, 2011) which, based on historical earthquake monetary loss estimations and average annual wages per capita, makes comparative assessments of earthquakes that occurred between 1906 and 2004.

Still, none of the above mentioned research results have been explicitly integrated with the estimations of damages and losses in the capital stock and therefore, their relevance in the medium and long term for prosperity and development has not yet been assessed.

2.6 The acceptable risk

Because of the increasing number of available risk assessments and tools, considering either natural or anthropogenic events, defining what an acceptable risk level is has become a whole study field. Although it is not an innovative concept (Starr, 1969; Fischhoff, 1994; Cardona, 2001), there is not a formal definition of it yet and depending on what is being assessed, different ideas need to be addressed and the question remains if whether there is (or should be) an acceptable risk. The acceptable risk is an ambiguous concept since what can be a large risk for some person (or some enterprise) can be acceptable for someone else; because of this, a good approximation to it is based on the concept that it cannot be defined but analyzed (Berliner, 1985).

Mankind has always lived together with risks of different types and the complete avoidance and/or mitigation for most of them is a virtually impossible task. Seismic risk is clearly not the exception, where even with a proper use and enforcement of building codes, some damages and losses in properties and occupants will always occur (Wein and Rose, 2011). Although the topic has not been addressed in an explicit and direct way, several decisions, made in the form of earthquake resistant building codes, have set a target or desired performance level.

The issue of how controllable a risk is plays a fundamental role in the definition of what is acceptable or not. Once there is a good understanding of the causes and drivers of risk, and the distribution of benefits and costs associated to that control is assessed, decisions can be made. In earthquake engineering, with todays' understanding not only on the earthquake occurrence pattern but on their effects on the built stock, structural behaviour and performance, a collapsed building is to be seen more as a crime scene than as a result of a natural phenomenon. To date, there is neither a standard nor a consensus on what can be a measure to assess seismic risk and define and monitor an acceptable level.

Defining an acceptable risk level requires that it can both be measured and understood. A definition and selection of what is intended to be measured and the way the threshold level is to be set is required beforehand, leading also to the question of what can be considered a good enough risk assessment. Risk perception and communication among the public is a difficult task to be developed since for the case of extreme events there is the bias in the understanding of the difference between the time of occupying a place and the one associated to the occurrence of the extreme event. Many times, the occupants have the false belief that both times are disconnected and, therefore, it is something that will not happen to them (Froot, 1999).

Protection demand by the public increases with the income per capita, but also, the acceptable risk decreases with the number of exposed people (Starr, 1969) and this leads to an important characteristic of the acceptable risk: it is not constant and its definition must be assessed and updated on a regular basis. Considering that, in general terms, global income per capita is on a constant increase and there is also a clear demographic growth, the protection demand will change and, therefore, if this is something that is to be explicitly addressed, a transparent criterion is to be defined. Several other factors are also involved, such as how controllable the risk is, the associated costs to reach certain acceptable level and the potential benefits of having reached them (Cardona, 2001). Regarding the costs, one of the questions that needs to be answered is how much is society willing to pay for safety? (Starr, 1969). Or seen in a different way, how much should society pay for safety? (Rosenblueth, 1976a). Both questions are clearly related to awareness and perception and a definitive answer has not yet been defined.

The definition of an acceptable risk has an important societal implication sinc,e first of all, it is a decision that can affect many people who lack the technical background and knowledge to make it by themselves, a fact that makes them trust, in a blind way, experts and their criteria. Second, it defines a threshold where anything above that level is considered good (Cardona, 2001; May, 2001) and thus needs to explicitly release responsibility on the person who made the decision even if damages and losses occur. It is, therefore, an implicit social agreement on a measure that applies for everyone but is not to be decided by everyone, requiring then a high degree of transparency.

If an acceptable risk level is selected, it should be flexible over time and subjected to periodical evaluations (Fischhoff, 1994; Cardona, 2001). Even if the technical aspect of a risk evaluation plays a fundamental role in the definition of a possible acceptable risk, it is not the only aspect to be considered (Renn, 1992) and, as mentioned above, other contextual aspects related to social, economic and risk aversion characteristics are to be included in the discussion.

Finally, a question that may arise when having defined an acceptable risk level is: who is to pay for the costs of mitigating risk when the actual risk conditions exceed the selected threshold? Should the mitigation measures be mandatory or voluntary? (Kunreuther and Kleffner, 1992). The response to those questions can be understood as to when to pay for the feasible losses since the following questions must be evaluated to see what is better: paying today to avoid future losses that may not occur? Or paying later the cost of the induced damage because of an earthquake knowing that access to funds, if not previously arranged, is a timely and costly task? Later, in this context, can mean next hour, next day, next week, next month or next generation.

Chapter 3

VIEWS ON THE ECONOMIC IMPACTS OF EARTHQUAKES

3.1 Summary of some macroeconomic metrics

Before analysing the different views of the negative or positive economic impacts of earthquakes, a summary of some macroeconomic metrics that can be relevant and useful to assess and monitor the impact of natural catastrophes is presented herein.

A good starting point is to clearly differentiate flux from stock metrics since this is relevant in what is being captured and assessed, especially in the aftermath of extreme events. Regardless of a metric measure a flux or a stock, it is worth bearing in mind that all economic statistics are imperfect and that different methodologies to estimate the same value exist and are usually employed. A similarity between these methodologies and the probabilistic risk assessment framework used in this thesis is that their objective is to provide orders of magnitudes for the economic performance and situation for the chosen geographical unit of analysis.

GDP, public deficit and investment reallocation are examples of flux metrics that besides having monetary units they also have an associated temporal dimension. These are usually expressed in terms of monetary units per year even if, for comparison and monitoring purposes, trimestral evaluations are performed.

Human and physical capitals are examples of stock metrics which are the result of the economic flow over time; these are measured at a specific moment and thus are expressed only in monetary units. These are the values usually included in annual economic reports which reflect the wealth at a specific moment in time of a country.

Stock metrics have the objective of measuring wealth and are affected by the incoming flow as a result of new investments as well as by the depreciation of the capital. The stock metrics are appraised at a specific time and refer to the value of an asset in a specific temporal point. Stock is usually appraised as if the good had been bought at the moment of the analysis (regardless if new or used) and, because of that, in some cases, capital stock has been used as an indicator for the estimation of the monetary exposure to natural hazards (CIMNE and Ingeniar, 2015; De Bono and Chatenoux, 2015).

Capital stock can be divided into three categories: 1) produced capital, 2) intangible capital and 3) natural capital. Among them, for the estimation of economic damages due to earthquakes, generally only the first one is considered. Some metrics that help understand the behavior of the capital stock are the gross fixed capital formation (GFCF) and the overall capital formation (CF). Both are flows where the first one is a metric of the gross net investment in fixed capital, which is basically physical assets that are not used in the production of goods, whereas the second is equal to the total GFCF but also considers changes in the inventories, acquisitions and disposals.

Among the existing macroeconomic metrics the following three are considered by most of the economists as the most important (Mankiw, 2014):

- The gross domestic product (GDP)
- The inflation rate
- The unemployment rate

GDP is usually reported at a national level, although it can also be found disaggregated at subnational or urban level. It can be defined as the total income obtained in the national territory added to the income generated by foreign production factors. Also, because of the characteristics of an economy, it can be defined as the total expenditure in goods and services produced in the national territory (Mankiw, 2014). From the previous definition, it is understood that GDP can be both a metric of income or expenditure based on the idea that, within an economy, what is expenditure for one person is income for another and, at the end of the process, there must be a balance.

GDP is also considered to be the most generic indicator of the current economic situation because of its capability of summarizing the monetary value of the economic activity during a defined timeframe, usually set in a year. GDP is estimated as follows:

$$GDP = C+I+GE+NE \tag{3.1}$$

where C stands for consumption, I for investment, GE for government expenditure and NE for net exports. All four components are important and are related to different sectors of the economy, and the sources used for their estimation range from tax revenue data to statistical data inferred from official surveys on production and expenditure. Consumption is comprised by the set of goods and services purchased at household level; investment captures the purchase of goods that are to be used in the future; government expenditure groups the goods and services purchased by the public administrations excluding some social expenditure like retirement pensions; and, finally, net export accounts for the international trade by adding the goods and services sold to other countries (exports) and subtracting the value of goods and services acquired from other countries (imports). Among the four components of the GDP, the consumption component is the one that generally contributes the most to the total value. In some industrialized countries it can account for up to 2/3 of the total GDP (World Bank, 2011).

It is important to clarify that within the investment category, only goods and services that generate new capital in the future are included; that is, the purchase of existing goods that provide an economic benefit to the buyer but that in economic terms represent only a money transaction, are left aside. This last fact is important when interpreting the behavior of an economy following the occurrence of an earthquake as well as the reason why the GDP value tends to increase in the medium and long term pulled by the reconstruction efforts.

Once the GDP has been estimated, the normalized value by inhabitant is usually estimated and reported, denoted as GDP per capita. This indicator is to be understood as a mean expenditure measure and is used mainly for comparison purposes. It is worth mentioning that this metric assumes an equal distribution of the GDP among the total number of citizens leaving aside inequality factors. This is an important consideration when using this indicator for the estimation of the average annual lost production due to premature mortality due to earthquakes using the methodology proposed in Chapter 5 since under the egalitarian ethical framework considered herein, it is assumed that all lives have the same value and contribution to production regardless gender or age (as long as they are within the working age range).

The inflation rate can be defined as the general increase of prices of goods and services within a market during a timeframe, again, usually set in one year (Mankiw, 2014). This increase of prices is, of course, translated into a decrease in the purchasing power since with the same amount of money less goods and services can be purchased as time passes by. Managing inflation is one of the main tasks and challenges of central banks and it is usually done by modifying and setting interest rates aside from printing money (this is the reason why inflation is also considered as a tax for holding money). Most governments nowadays attempt to have a positive, continuous and controlled inflation rate since it has benefits in reducing economic crisis risks (Moss, 2014). A negative inflation rate is known as deflation and, in spite of the intuitive advantages associated to the certainty that money will cost more in the future (which can have important implications in the saving rates of an economy), it has several disadvantages that can threaten its good performance. An immediate consequence is the decrease of the overall demand and with that, industries and enterprises have lower benefits because of the required reduction of prices to adjust the supply with the new demand level. Depending on the conditions and length of the deflation, the decrease in prices can be translated into an increase of the unemployment rate, and people classified in this group will also reduce their expenditure given their lack of income, and therefore the demand will continue decreasing in a continuous and dangerous cycle.

Finally the unemployment rate estimates the ratio of people who have a job to the total population within the working age (e.g. OECD defines it between 15 and 64 years) having the proper conditions and will to perform it (also known as the active population). Unemployment is considered the biggest macroeconomic problem which has not only monetary but also social consequences; however, having unemployment is unavoidable since in every free market economy there is always unemployed people (Mankiw, 2014). In economic terms, and according to the Okun law (Okun, 1962), an increase of 1% of the unemployment rate represents approximately a 2.5% decrease in the overall GDP for a given year.

It is important to discuss all of the topics above since nowadays it is common practice to compare physical risk results with certain macroeconomic indicators. This has been the case of the results provided by GAR13 and GAR15 (UNISDR, 2013; 2015a; Løvholt et al., 2015), where the case of Japan provides a very good example on interpretation of the results. The multi-hazard *AAL* for Japan, when compared to the GFCF, represents an important fraction meaning that repairing the damages and losses in the capital stock require more efforts than the ones focused solely on capital formation.

3.2 Different perspectives

After having mentioned and briefly described some macroeconomic metrics that can be relevant and that have been used for normalizing and comparison purposes within the disaster risk reduction (DRR) field, this section summarizes the views of different authors that over more than 40 years have provided important research on the impacts of earthquakes, among other low frequency and extreme events, upon the economies at national level.

It is evident that after an earthquake hits an area, aside from the destruction of the existing stock, there is a set of social impacts as a consequence of its occurrence. Loss of lives, injuries, business disruption, failures in communication systems and interruption in lifelines add to the overall secondary or indirect losses. Earthquakes, as most geological hazards, have a high impact only in the infrastructure sector and not so much in others such as agriculture, which narrows the impact studies whose main findings are presented next.

Even if associated to destruction and devastation, different authors have found that depending on the location of the earthquake (i.e. urban or rural area), its magnitude, political stability conditions during and after the emergency and the geographical diversification of the industries and working centers, among others, these events can also provide opportunities to improve the economic development and performance, deriving in an overall stronger economy in the medium and long term (Albala-Bertrand, 1993; Crespo et al., 2008; Hallegate and Dumas, 2009; Loayza et al., 2009; Hallegate and Przyluski, 2010; Ma, 2011). When assessing the economic impact of earthquakes, the positive or negative answer to the question has to be determined, and it has been suggested that this task is to be performed in the medium term, that is, between 18 and 24 months following the event (Benson and Clay, 2003; Jaramillo, 2009) given that the overall effect of geological events and the set of activities that are triggered by it, such as reconstruction and repairing, can only be observed by then.

An aspect that is also a differentiating factor in the scope and extent of the economic impact is the type of area that has been affected. For example, earthquakes in urban areas can cause serious stress at national level since industries and institutions, both public and private, are in many cases concentrated there, and by slowing down or even shutting down their operation, it can reduce the life standards, income, outcome and expenditure at country level (Bolt, 1991). An earthquake with the same characteristics occurring in a place where the industrial and economic activity is not as relevant at a national scale as it is in the case of a main urban centre, will cause a negative change on the economic development path of the country despite the fact that it will generate local consequences.

Another topic to be taken into account at this stage is the access to external aid and economic loans negotiated in the aftermath of the event. External aid has proven to have in some cases negative consequences since some governments, trusting blindly that they will receive them in case of an emergency, find and incentive to dismiss and ignore *ex-ante* DRR measures, even if they know in advance that its availability is limited and that its arrival is usually delayed (Gurenko, 2004).

This is also translated in the way citizens feel that they will be assisted after the event thus disrupting the promotion and purchase of risk transfer instruments. Governments that end up paying for the non-insured losses create a bad incentive not only by making people take a relaxed attitude towards risk, but also by providing an implicit invitation to continue using hazard prone areas, actions that of course will limit the application and development of DRR actions (Kleindorfer and Kunreuther, 1999; Moss, 1999).

From a pure economic perspective, an earthquake can be defined as an event that causes a perturbation in the normal functioning of the system with negative impacts in assets, production, consumption and employment (Hallegate and Przyluski, 2010), and after their occurrence, a large set of activities are required for the recovery of all four of the above mentioned aspects which, as expected, require resources that are limited and scarce. For all these stages, it is also important to identify when the resources are needed because the temporal dimension of the deposits and funds needs to be considered. Most of these funds are required for the reconstruction phase (Ghesquiere and Mahul, 2010) and it is during this phase that there is the big change in increasing productivity levels, improving capital, moving forward to a better economic performance and even reducing the disaster risk conditions if a build back better practice is well implemented. This last concept refers to the practice where reconstructing the vulnerability is to be avoided.

The lack of consensus on this topic has also derived in a series of different proposals on how governments should prepare and react against natural catastrophes. The Arrow-Lind theorem (Arrow and Lind, 1970) states that governments should take a neutral position against different types of risks, in which disaster risk is included, and therefore avoid buying protection in terms of insurance because its portfolio is well diversified. This is a condition which holds for industrialized countries with an extensive territory where the unaffected areas can subsidize with their income the affected ones. Nowadays, even for countries with the characteristics mentioned before, it is not considered appropriate nor sustainable to lack financial protection against natural catastrophes, especially when it is clear that governments are natural reinsurers, or reinsurers of last resort; this occurs because governments are held responsible for paying not only the losses that occurred on their assets (bearing in mind that they usually own large amounts of assets) but also of assisting the affected in the low-income group, the well-known contingent liability (Polackova, 1999). Different studies have led to the conclusion that the application of the Arrow-Lind theorem is far more particular than general (Mechler et al., 2006; Hochrainer, 2009; Hochrainer et al., 2013). For example, in cases where the economy relies in only some sectors, any damage that causes serious losses and interruptions on it can heavily threaten both the short and medium term economic performance.

Other aspect to be considered is the strength of the financial markets. If, for example, there is a weak financial system, any debt is to be resolved by having access only to internal financial sources and can cause an important imbalance in the income distribution. It is well-known that small economies are less diversified and, in the case of small countries, the total area does not even allow for a geographical diversification of the exposure. This gives it a high chance of having damages everywhere after the occurrence of a single event and thus any decrease or damage on the capital stock is immediately translated into an increase of the external debt (Moss, 2014).

Exposure to seismic hazard has nothing to do with development and in the cases where it exists, it should be managed and not avoided. Today's understanding on it, although still incomplete, allows for developing studies that provide robust results and metrics that can be incorporated into comprehensive DRM schemes and are useful for the design and implementation of financial instruments for risk transfer and retention. Different studies have provided ground reasons on why governments should not be neutral to disaster risk, covering aspects such as the abrupt changes in the fiscal debt and payment balance at national level because of the important modifications expected in the domestic savings rate and tax revenue (Hochrainer, 2009; Hochrainer et al., 2013). Moreover, by taking this neutral approach to disaster risk, there is the chance to aggravate the unbalance in the income distribution, a major challenge in sustainable development.

The views on the overall negative consequences are presented next and in summary, they share the idea that once there damage has occurred on the capital stock, the necessary adjustments in macroeconomic terms for their repair and recovery make it impossible for any country to catch up with the initial economic development path. After reviewing these ideas, the opposite views that consider earthquakes as events that can provide opportunities for boosting the economic activity and whose benefits can be seen in the medium and long term (although causing important damages and losses on the exposed assets) are reviewed. However, for this to be achieved, different conditions are required not only in terms of emergency attention but also in the planning and execution of the reconstruction phase, not losing sight of the fact that even if it is true that there are several macroeconomic metrics to assess the performance of the economic activity at country level, not all of them capture the same aspects and neither can capture all relevant aspects at the same time.

3.2.1 The negative consequences of earthquakes

Earthquakes are events that depending on their characteristics in terms of magnitude and location, can generate damages and casualties which need to be faced and tackled in an almost immediate way. The attention to the emergency requires funds and besides the damage extension, the governmental preparedness also plays a fundamental role. In cases where no funds are available for immediate use on these urgent tasks, the situation can cause enough pressure at a governmental level for the deviation or reallocation of funds and the need to look for other urgent financing options. The creation of new taxes is one of these alternatives which is often preferred, as occurred in Colombia after the 1999 earthquake.

Budgetary reallocation has been, for a long time, the primary response to natural catastrophes by governments (Benson and Clay, 2003) even though it has been highly criticized. However, in countries where there are neither *ex-ante* financial protection strategies, nor timely fund transferring mechanisms to cope with the emergency response, it is unfortunately, still, the only viable way. In the case of new taxes, after the January 1999 earthquake in Colombia, a temporal tax was created with the specific aim of collecting funds for the reconstruction of the affected region. It was fixed on 2‰ of each banking transaction, and today, more than 15 years later and when the reconstruction has finished, it is still in place and with a higher rate of 4‰. Any of the two above mentioned choices have always left the sensation of having changed the long term even if they can be classified as acting in the short term.

The condition of the economy of the affected country at the moment of the earthquake also has to do in the overall economic impact. This is not to say that there are good or bad times to suffer an earthquake, but that in the case where the economy has been performing well and wealth has been created, these hard efforts can vanish within seconds, whereas in the case of having an economic crisis at the time of the event, the poor economic performance will perpetuate for a longer time. In any case, the disturbance of the economic system will exist and unfortunately, it is only when the importance of having a well-established DRM strategy and comprehensive scheme is acknowledged.

In general terms, what occurs immediately after an earthquake can be summarized as damage in the existing capital stock, which is later translated into a decrease in productivity as a consequence of an economic contraction, a situation that is finally reflected in a decrease of economic growth. The latter in developing countries is highly sensitive to natural catastrophes (Loayza et al., 2009) and it has also been estimated that the rate is lower in countries that have had natural catastrophes before (Benson, 2003). This value goes close in hand with the inflation rate, proven to increase in the short term as a consequence of the occurrence of an earthquake. An unstable economy will always fail to attract foreign investment and in the case of earthquakes, the sole existence of disaster risk (which does not mean the occurrence of an event) is to be considered as a negative incentive for future investments in all sectors (Hallegate and Dumas, 2009).

Changes in the fiscal balance are caused in the short term by the pressure imposed by the damaging event in the public finances which, as mentioned before, can be classified into emergency assistance, immediate reallocation, shelter deployment and reconstruction planning. This variation in the fiscal balance occurs as a consequence of a decrease in consumption and investment, increase of fiscal deficit, disequilibrium in commercial balance and the unavoidable decrease in the tax revenue (Mechler et al., 2006).

All disasters have a political dimension (Hochainer, 2009; Woo, 2011) and additional to a transparent political economy, it is also desirable to have political stability. The first one is very useful for the planning and implementation of DRM strategies in different fields (Gurenko, 2004), whereas the second one is one of the conditions needed for a good economic performance following the extreme event (Ma, 2011). Unfortunately, catastrophes still create political visibility and the management of the emergency has served in many cases, both in developing and industrialized countries, as windows of opportunity for the misuse and misallocation of funds with objectives other than the humanitarian ones. This is one of the causes for the lack of political will for the implementation of strong DRM policies where none of these aspects is left to luck and where they are to be acted upon independently of any political or ideological position, leading to a situation where the plan for action is openly available, known in advance and clear for every citizen.

The occurrence of a catastrophe can delay the construction of basic infrastructure in different sectors and this, of course, can have important effects in development (Benson and Clay, 2003), especially in interconnected and globalized economies as the ones that exist today. One good example of this is Colombia and the floods that affected the country in 2010 and 2011, just months after a new government had taken over. Following a successful economic development and growing path which started in 2002, the country had started the process of signing several free trade agreements worldwide which required the construction and maintenance of important transportation infrastructure. This was correctly and timely planned but changes were needed when important industrial and agricultural areas of the country were flooded at different locations at the same time, and resources for the attention of the emergency needed to be reallocated from several sources. Free trade agreements were still held but the lack of appropriate transportation infrastructure has now proven to be an important burden for improving the international competitiveness of the country.

The reduction in the economic flows such as consumption and investment because of damages in the capital stock can modify negatively the economic development of a country even in the long term (World Bank, 2003) and some authors have shown, by means of economic calculations, that once there has been damage in the capital stock, the affected economies have found it impossible to move back to the pre-event economic growth path (Noy and Nualsri, 2007). This is not the only consequence of the affection on the capital stock since once it has been reduced, following the law of demand and supply there will be an increase in the real price of renting since the capital equilibrium point has shifted (Mankiw, 2014).

3.2.2 Earthquakes as opportunities for development

This section presents the views on extreme events as opportunities to boost some economic sectors which derive into a better economic performance. A good starting point for this discussion is the review on why a natural catastrophe is highly unlikely to become an economic catastrophe. Albala-Bertrand (2006) has led this train of thought and has proposed that the following three conditions need to exist, at the same time, for an economic catastrophe to occur:

1. The direct effects in the affected stock are large and are geographically distributed.
2. The indirect effects are out of control and,
3. The institutional effects are devastating and only external aid can be helpful.

If any of the above mentioned conditions does not exist, then it is assumed that losses in the capital stock are not translated into important effects in terms of economic growth, and a moderate expenditure focused on recovery and reconstruction is enough to avoid the fall of the economy.

Regarding the first condition, it is also stated that most of the geographically localized catastrophes are also confined in economic terms and thus the second and third conditions are almost impossible to occur. Nevertheless, in the case of earthquakes, a geographically distributed devastation is not impossible, giving the possibility for the second and third conditions to occur. Nonetheless, under this theory, given that the economic catastrophe is highly unlikely to occur, what is to be expected following a natural catastrophe is an increase in GDP, capital formation, construction and agricultural production and stability in the inflation rate (Albala-Bertrand, 2003; Crespo et al., 2008; Loayza et al., 2009; Noy, 2009; Ma, 2011).

The main reasons for natural catastrophes to be considered as positive perturbations to an economic system depend on the opportunities to update the capital stock and adopt new technologies, under the framework of the Schumpeterian creative destruction (Crespo et al., 2008). Updates of the capital stock can take many forms and cover different sectors; for example, in the case of the public sector, it can come in the form of adaptation of public infrastructure such as bigger and better schools, administrative public offices and hospitals to address new needs and better accommodate the users. Those updates and improvements in the capital stock can leave room for higher economic growth rates in the medium and long term that are to be also reflected in a higher GDP per capita (Crespo et al., 2008).

Additionally, the update and/or replacement of the capital stock can boost the investment in the construction sector, one of the most important in any economy for the amount of labor force it requires and thus it is to be reflected as a positive effect in the short term. These investments are also a consequence of the expenditure increase in both public and private sectors (Ma, 2011), an effect that is better differentiated and observed in developing countries and that has proven to provide important opportunities for the attraction of new capital fluxes from national and international sources in terms of investment (Mechler, 2009), which under the GDP estimation scheme presented before are to be considered as a positive impacts in the industrial growth (Loayza et al., 2009).

The replacement of old production technologies can also derive in capital improvement by first, increasing efficiency and productivity and second, by activating other sectors of the economy with higher productivity levels than the previously existing ones, a situation which can end up in a better overall economic path if compared to the pre-event phase. So far, the above mentioned reasons to expect a better economic performance in the medium term following an extreme event seem fairly logical. Nevertheless, there are serious difficulties in their implementation which depend not only on the social but also on the political context of the affected area; it is also ignored that behind the new capital stock created in the reconstruction there are important damages, intangible consequences and human suffering which are not captured by any of the economic metrics.

Regardless of the reason for a good economic performance after an extreme event, there is no evidence that the risk neutrality at a governmental level has posed any significant advantage and/or saving without losing sight in the fact that there are several specific conditions that need to exist for a better economic performance. One of them has to do with the attempt to recover not only the damage stock but the fluxes guaranteeing at the same time their sustainability. A needs to have a stable and strong political economy country to be able to attract new investments, and it has been recognized as a target closely related to DRM (Gurenko, 2004).

As it has happened in different stages of economic history, new technologies can find resistance since its implementation will benefit some while it can harm others. Additional to these conflicts of interest, in most cases the adoption of new technologies is not possible in developing countries due to the lack of time and financial capacity (Benson and Clay, 2004). Most producers, but mainly those classified as small, cannot afford long disruptions in their business and thus they attempt to restore their production as soon as possible, leaving no space for the evaluation and selection of newer technologies, even if they can provide a better future performance. Morevoer, when adopting new technologies, knowledge transfer in its use is required and when they are complex, qualified workers are needed which are not necessarily available, causing them to reject the adoption of it.

Differences in the impacts on developing and industrialized countries have also been explored, and it is evident that there is a disproportionate distribution of the loss toll, in both physical and human dimensions. It is evident from Figure 3-1 that earthquakes have occurred and will continue occurring both in developing and industrialized countries so the differences are not a matter only of the seismic hazard level but of development and preparedness.

Poor economic performance in the developing countries is associated to the destruction of the capital stock whereas for industrialized ones the loss of technological and human capital is more relevant (Mechler, 2009); the latter is also closely related to the unemployment rates observed before and after the event which have been identified as another of the reasons that can explain the differences in the results. Nevertheless, there is a close relationship between capital and human stock since the mortality due to earthquakes is highly correlated to damages in the first one; it becomes evident then that by improving the conditions of the first one there will be a direct effect in terms of the reduction of the negative effects, such as mortality, in the second one.

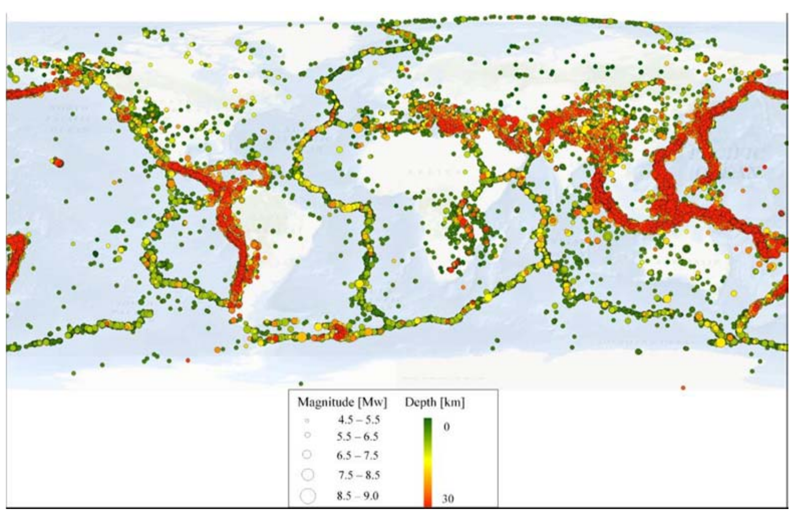


Figure 3-1 Earthquake catalogue with M>4.5 and 0-30km depth (from: CIMNE and Ingeniar, 2015)

3.3 What can be affected

To better understand what the effects of earthquakes can be in terms of economic impacts, it is good to explore which of the components of an economy, at a country level, can be affected and how. It was mentioned before that earthquakes cause perturbations on the economic system with consequences on assets, production, consumption and employment and it was also mentioned at the beginning of this chapter that GDP was considered as the best economic indicator to assess the results and behaviour of an economy at a specific time. Nowadays, and closely related to the risk communication process, it is common to see both retrospective and prospective risk assessments normalized by the GDP of the affected area (Cardona et al., 2014; CIMNE and Ingeniar, 2015; SwissRe, 2015) and, therefore, it is also important to understand what can and cannot be captured by it.

One task is to estimate the ratio between the loss and the GDP which serves to see the overall significance of the event at a specific time in an economic system, and another one is to assess the behaviour of the economy once the event has occurred based on the same metric. For the first case one of the factors that define the suitability and relevance of doing this comparison has to do with the geographical, economic and sectorial diversification that exists in the country under analysis. A wrong message can be conveyed to stakeholders if, for example, damage to property and business disruption (among others) are severe at a local scale, causing severe economic and social stress to its inhabitants, but are not significant enough to have an impact in the country's GDP (Kunreuther and Michel-Kerjan, 2013). A low ratio between the loss and the GDP does not necessarily mean a good DRM practice but may only indicate a situation of a large economy with unequal income distribution and diversified production where those which are most vulnerable from a socioeconomic perspective are the affected ones.

For the second case, a series of comments and warnings are presented herein, starting again by stressing that GDP corresponds to a flux metric and what is damaged and destroyed by the event is a stock. Any variation in the GDP, either positive or negative, is obtained measuring only the flow of new production (Noy, 2009) and, therefore, the damages caused on the capital stock are not reflected in its value (Scholtens and Voorhorst, 2013). Furthermore, other loss dimensions different than the physical one are not captured within that metric such as the loss of lives and the individual experiences of the affected population (Ma, 2011).

A list of the macroeconomic measures that can be affected, both positively and negatively, is shown next with a brief explanation of the reasons for their variations according to what was explained before:

- *Consumption*: being in most cases the biggest component of the GDP, it is also one of the most affected measures due to the occurrence of earthquakes. The perturbation of the economic system is translated into a decrease in consumption of goods and services and can take several months for it to recover. As an example, the sales after 18 months of the Kobe earthquake represented only 76% of the value prior to the event (Horwich, 1997; Sawada and Shimizutani, 2011).

- *Investment*: it is also a flux and it is expected to decrease in the short term and then increase in the medium term (defined as the following 18 to 24 months) boosted by the reconstruction efforts. The overall positive or negative impact on this variable depends on the planning, quality and amount of attracted capital in the affected area (Auffret, 2003) which depends highly in the political economy and stability. Following an earthquake, this is the variable that can increase significantly the future stock and on which most of the DRM efforts should focus with the aim of promoting and creating incentives for practices that follow a build back better approach.
- *Government expenditure*: since governments are among the parties who pay the most for the risk (Linnerooth-Bayer and Amendola, 2000) and a large response is expected from them after a catastrophe, it is one of the GDP components where important variations are expected. Governments are not only owners of large amounts of assets but act as reinsurers of last resort for the low-income population. An increase on the government expenditure is expected in the aftermath of an earthquake and this is to be translated into a positive perturbation in the aggregated demand (Mankiw, 2014).
- *Net export*: the destruction of capital stock and the associated productivity reduction can cause the increase of imports, as well as the decrease of exports for problems in production, supply and transportation in the short term that follows a catastrophic event (Rasmussen, 2004).
- *Saving rate*: even if an earthquake can destroy part of the capital stock (which is expected), a decrease in the production level in the immediate aftermath can generate a period of high economic growth if saving rates do not change (Mankiw, 2014). For this to occur, several *ex-ante* strategies complemented with an efficient and strong financial market need to exist; for the case of developing countries, this is nothing more than theoretical. If those strategies do not exist, overall saving rates are expected to decline as a consequence of the decrease in income and increase in investment forced by the reconstruction process.
- *Tax revenue*: this is a factor that always changes following an earthquake. On one hand, and in order to cover the reconstruction costs, governments can make the decision of creating new taxes, even under a temporal basis. On the other hand, tax revenue from other sources such as consumption and property usually follow a decrease

process, having important consequences in the fiscal debt and payment balance at country level.

- *Inflation rate*: inflation rate depends highly on the interest rates which, on the other hand, are also closely related to the government expenditure. When there is an increase in the latter, there is always an increase in the interest types and if this happens the inflation rate does the same. Usually after an earthquake, while the market stabilizes again in terms of demand and supply, an increase in prices of construction materials and labour force in the sector occurs. This is known as demand surge and it has been established that it can increase the rebuilding costs up to a 20%. This is a reason for its rapid increase in the short term, but later on it tends to gradually stabilize again (Ma, 2011). Decisions made by central banks on the interest rates to be used during the reconstruction phase are critical to avoid super-inflation processes that can jeopardize the overall performance of the national economy.
- *Stock market*: earthquakes have shown to have negative effects on the local stock markets (Scholtens and Voorhost, 2013). It has been observed that it is sensitive only to the occurrence of the event and not to its characteristics in terms of location and magnitude. Losses between 6 and 12% have been observed within a 3-days timeframe in the stock prices and these values are similar in developing and industrialized countries, what can be understood as a sign that markets are highly globalized today.
- *Real estate mortgages*: similar to what occurs after a real estate bubble bursts, the occurrence of an earthquake can decrease the commercial value of property if damaged. Depending on the loan conditions, the owner may prefer to give away the house to the loaner since the debt is much higher than the real cost. This fact, repeated for a considerable number of houses, can pose a serious challenge to housing, construction and baking sectors as well as to the financial markets.
- *International trade*: in a highly globalized economy such as the one that exists for most of the free market countries, physical damage of the local economy is then transmitted and distributed to other geographical regions, industrial sectors and economic domains as was largely observed in the Tohoku (2011) earthquake and the Thailand (2011) floods (Li et al. 2011).

All the above mentioned variables have the common characteristic that they fail to address and account for the human dimension of the losses. Mortality is not implicitly considered in any of them and this of course poses a difficulty for the integration and understanding of all relevant dimensions.

3.4 Earthquakes and sustainable development

This section examines a series of actions regarding seismic risk management which are closely related to sustainable development, covering both *ex-ante* and *ex-post* stages. Sustainable development has been recently recognized as a positive outcome of an effective DRM strategy; nevertheless, the latter is not the only determinant for it to occur. In 2015, 17 goals on sustainable development were established by the United Nations as a continuation of the Millennium Development Goals set back in 2000, where significant advances have been observed in terms of overall poverty decline, access to drinking water and education (UN, 2015). Beforehand, it is acknowledged that disasters can significantly impede progress towards sustainable development (UNISDR, 2015b).

Among those 17 goals, one refers to sustainable cities and communities, encouraged by the fact that, until today, around 3.5 billion people live in urban areas and 95% of the urban expansion in the following decades is expected to take place in developing countries. This goal has different associated targets, and one of these specifies that in a timeframe of 5 years from now, there should be a substantial increase in the number of cities that adopt and implement policies and plans aligned with the Sendai Framework for Disaster Risk Reduction - SFDRR (UNISDR, 2015b). Another one states that in 15 years for now, there should be a significantly decline in the number of deaths and affected people by disasters.

Even if the sole recognition of disaster risk as an important component of sustainable development is an important gain, it also needs to serve as a motivation to continue in the development of policies, plans and capacity building processes to integrate in an appropriate way the results and outcomes of hazard, vulnerability and risk analyses, going far beyond the risk identification stage.

In a world where the exposure is increasing at a tremendous rate (as shown in Chapter 1), it is a challenge that the expected losses and overall affected population do not follow this same trend. If this is allowed to occur, those damages and losses can mine the progress made so far as a result of the many different efforts made in various aspects towards sustainable development, and therefore, special attention and actions are needed. The fact that the understanding of the potential consequences of earthquakes in the built infrastructure and its occupants has not been yet translated into concrete and continuous actions, it is also of interest and has been a topic of large debate, the fact that despite the numerous available risk assessments they have not derived into concrete actions yet.

In hand with sustainability in the DRM field, the concept of resilience usually appears. The definition used in this thesis for this concept at a community level, acknowledging that there are some others with specific differences, is: the adaptive ability of a socio-ecological system to cope and absorb negative impacts as a result of the capacity to anticipate, respond and recover from damaging events (Cardona, 2001). Several methodologies have been developed for its assessment and quantification and, among them, the proposed one for urban areas by Cardona (2001), Carreño (2006) and Carreño et al. (2007; 2012) are considered as useful for a complete risk assessment, which not only accounts for the physical risk but also for the lack of resilience and social fragility conditions. Results obtained under these approaches are useful for a complete identification of the risk drivers and are therefore useful tools for both stakeholders and decision-makers in the process of defining strategies and actions. These multidisciplinary risk assessments, which follow a probabilistic and holistic approach, are determinant for a full understanding of the risk panorama and its development should be promoted.

The urbanization process that has occurred during the past 30 years has caused that in today's world at least half of the population lives in urban areas. Aside from providing better chances of accessing better job opportunities and improving economic conditions for many people, this process has also significantly increased their exposure to natural hazards. This is an increase that has been far faster than the mitigation of the vulnerability (UNISDR, 2015b) leading to a complicated and pessimistic disaster risk panorama where, unfortunately, the worst is yet expected to come. In many cases, this urbanization process has obliged the new inhabitants to use land located in hazard prone areas given that it was the only available space; in other cases, they have used these spaces, even if they are aware of the risk which had been properly identified as a result of an acceptable risk evaluation and balance as further discussed in Chapter 4.

In the developing countries, economic and human losses are still extremely high, even when significant advances have been made in terms of the understanding of the natural phenomena and the potential destruction they can cause. It is totally unsustainable and also unacceptable that a casualty figure of 9 after an earthquake in Spain is cause of serious and extensive reflection in the community, whereas a casualty figure of hundreds, if not thousands, after an earthquake in a developing country is still understood, at the local level, as simple bad luck without a proper accountability.

Mortality is among the most critical consequences of earthquakes not only because the loss of lives is to be interpreted as a failure of the social system to guarantee safe dwellings to citizens, but also because it is highly concentrated among the poorest. In this low-income category, additional to the human suffering, the chance of the breadwinner dying is high and in the case that this occurs, families continue trapped in the poverty cycle from where it is extremely difficult to get out.

A common reason among authors that find earthquakes as opportunities for an improvement and update of the capital stock, for the economic performance to improve in the medium and long term is the quality of the reconstruction (Jaramillo, 2009). Of course, that quality will depend on the planning framework which, at the same time, is directly correlated with the risk understanding, legislation and perception in the affected area. A build back better approach is always needed in order to avoid the reconstruction of vulnerability which under todays' conditions of increasing exposure will unavoidably derive in an unsustainable higher disaster risk level.

It has always been said that investing in DRR will always yield a good return. Even if the potential benefits of corrective measures can be assessed by different techniques (Smyth et al., 2004; Linnerrooth-Bayer and Mechler, 2009; Ordaz et al., 2010), what is to be a minimum investment on seismic safety has not been yet defined. Using the methodology proposed in Chapter 5 of this thesis, an order of magnitude of what is to be the minimum public investment in seismic safety, for corrective measures, can be obtained. Those results consider the implications on lost economic production as a result of premature mortality because of earthquakes and aim to recognize and to explicitly include its reduction in earthquake engineering legislation (e.g. building codes). Further exploring this idea, it would mean that the lower the earthquake mortality, the lower the required investment on corrective measures related to seismic safety. This, in other words, means that this is to be considered as a finite process and its implementation in the form of a public policy will allow talking about a horizon. For this to apply, every new structure and every reconstructed one must follow up to date requirements for, if not decreasing, at least maintaining the vulnerability level.

The benefits of a structural retrofitting program are evident and have been mentioned by several authors. Nevertheless, who is to bear the costs associated to it and the way it is implemented under a mandatory or voluntary basis is not yet clear (Zolfaghari, 2010). Even if homeowners understand completely the benefits of retrofitting in terms of lowering the expected damages and losses, they are only seen as a possibility and there is not a tangible benefit, therefore, there are not enough incentives to enrol on any of these initiatives. If the biased perception on low frequency events (the erroneous idea that "it cannot happen to me") is added to this, an explanation on why structural retrofitting schemes on private dwellings has not been successful anywhere in the world is found.

The way earthquake insurance premiums are calculated also make a difference in the risk perception. If a blanket premium is chosen for a specific portfolio, the differences of good and bad practices are not perceptible to most of the homeowners and this can also be a bad incentive to use hazard prone areas and also discourage owners to purchase insurance. More recent proposals consider the fact that the insurance premiums should reflect the risk levels even if that is done gradually as it is the case of the French Natural Catastrophe insurance system (Vallet, 2004).

Finally, it is important to mention that a change in the way donor assistance is given to both emergency attention and *ex-ante* activities related to DRR is also needed. For the first case, the economic loans which are negotiated and made available after the catastrophe can be classified as reactive and knowing about their availability beforehand has not provided major incentives for the development of plans in terms of risk mitigation and preparedness. A recent study by the OECD (Poole, 2014) proposes a set of different actions on how donors can engage with the development and use of different financial mechanisms ranging from traditional insurance/reinsurance schemes to more complicated alternative risk transfer instruments such as contingent credits, CAT-Bonds and other insurance linked securities (Cardona, 2009). The proposal considers different ways to promote a real partnership between donors and receivers ranging from complementary approaches, where a mere accompaniment in the risk-financing policy is to be developed, up to high level engagement where strong bilateral bonds are created. This progress made from the donor side in order to account not only for providing the needed assistance in a disorganized way, but to engage in terms of strong bilateral partnerships, can ensure that concrete objectives are met. Finally, by knowing in advance what the minimum investment on seismic safety is and also how those resources are to be used and allocated, it has the added value of helping a better expenditure policy of the resources into specific corrective activities.

3.5 Seismic safety, governance and accountability

Although seismic safety has gained importance and recognition in the recent past, it still lacks in many places the required governance and accountability levels for the appropriate development, application and enforcement of the actions required for an important overall increase. That a well-intended policy is developed is not by itself a guarantee of having a positive outcome, and the implementation phase has a lot to do in the final result, where it has also been noted that the implementation and intention gap can be, in many occasions, very large (Banerjee and Duflo, 2011).

To date, seismic safety has failed to prove efficient under a free market environment, and it is in those cases where there are issues that markets cannot solve and when the need for Governments to exist is evident. However, the mere existence of a governmental system does not guarantee by itself a proper functioning given that it requires the existence of good institutions to both promote and guarantee the existence of governance.

Governance influences the way in which actors at different scales have the will and possibility to develop and coordinate actions with the objective of achieving a defined goal. In the case of seismic safety, although the final target can take different forms, ranging from preventing collapse to protect lives and welfare, the way to define the steps and requirements is usually through building codes. Besides the political will, certain level of public awareness and understanding is required in order to be able to define politics, allocate and assign the necessary resources.

It is for the estimation of the minimum amount of public investment on corrective actions regarding seismic safety that the methodology proposed in this thesis intends to contribute, by providing a probabilistic framework for the estimation of risk considering the human dimension, which allows for a direct quantification, an essential step in disaster risk management (Cardona, 2009). An appropriate management has a lot to do with the existence of good governance and seismic safety, one component of DRR and DRM is not the exception.

Good governance comprises the parallel existence of transparency, broad participation, efficiency, responsiveness and accountability (UNISDR, 2011; 2013). In the case of the latter, the definition proposed by Olson et al. (2011) is preferred for the framework of this thesis, highlighting the importance of the obligation to explain actions and conducts by the actors to a forum, which at the same time may also bring up questions and require additional information to have the chance, at the end, to derive in positive or negative consequences. The availability and development of new ways to quantify seismic safety by means of probabilistic models that cover different dimensions such as the physical and the human dimensions, provide the chance to increase both good management through a better quantification and accountability, while at the same time helping to raise public awareness on the topics and thus improving the chance of having a better control by the so called forum.

Mainstreaming seismic safety is at the end a governance process which should promote the participation of all relevant actors on the technical side, and at the same time guarantee a proper articulation with broader DRR initiatives that have implications in the political, economic, social and environmental development. Nonetheless, it needs to be understood as a process whose results may not be observable in the near future, that is, the development and enforcement of a new building code is not going to be reflected in an immediate decrease of the physical vulnerability of the existing buildings, but only on the ones to be built according to the new rules. All these issues need also to be understood by the forum in order to control what is feasible to be monitored and avoid a myriad of queries and accusations against the actors that lack the sufficient robustness and pertinence.

Chapter 4

THE ACCEPTABLE RISK IN EARTHQUAKE ENGINEERING

4.1 Introductory remarks on the acceptable risk

In Chapter 2, different views on the acceptable risk concept were presented and in this chapter all those ideas are contextualized within the field of earthquake engineering. First of all, it is important to see that, even if in most of the legislation that applies today in earthquake engineering, the definition of an acceptable risk level has neither been explicitly included, nor mentioned, a set of actions and mandatory requirements have addressed implicitly this idea and, therefore, it can be said, without doubts, that the acceptable risk does exist in earthquake engineering.

Although the definition of an acceptable risk level is acknowledged to require a multidisciplinary approach where, additional to the technical information, social and economic considerations are to be also included, it is important to review how this concept has been addressed so far within the earthquake engineering field in terms of what has been achieved after its implementation and use and also how those considerations, different than the technical ones, have been addressed. The human being has always lived together with risks and the seismic one is not the exception; in reality, and due to the scarcity of resources, it is impossible to mitigate all of them and then the challenge, at societal level, is to manage and optimize their utility functions by at the same time providing some degree of safety to the exposed citizens.

What is too much risk is an idea that goes close in hand with how safe is safe enough and, although difficult to define and acknowledging the imprecisions existing in today's definitions, the safety levels that are inherent to any of the existing earthquake resistant building codes represent a quantification of the judgment of the experts (Ellingwood, 2001).

It is common to find in earthquake resistant building codes a set of minimum targets, applicable to new buildings, like the ones listed next[4]:

[4] Extracted from the Colombian earthquake resistant building code (NSR-10)

1. To be able to resist minor earthquakes without damage.
2. To be able to resist moderate earthquakes without significant structural damage but with some non-structural damage.
3. To be able to resist severe earthquakes with structural and non-structural damage without collapse.

Even if the definitions related to the earthquake size and damage levels are highly subjective (i.e. what is a *minor* earthquake or what is *some* non-structural damage), the third target constitutes the main pillar of the philosophy behind most current building codes that are focused in avoiding structural collapse, noting that it does not explicitly mention anything regarding protecting lives, heritage and/or wealth. Anyhow, by those requirements aiming to avoid a building collapse, implicitly they are protecting these three last mentioned categories.

The existence of mandatory building codes and their inclusion in requisites as the ones listed above, show that even if it has been a task done in an indirect way, governments and local experts have made a decision on what an acceptable risk level is. In all cases, building codes are used to define thresholds (Spector, 1997) and, in many places, such as in Colombia, legally speaking, a structural engineer who complies from the structural point of view with all their requirements, is dismissed of any responsibility after the occurrence of an earthquake despite the existence of other consequences such as damages to neighbouring properties.

Any update of the requirements included in earthquake resistant building codes apply only to new structures even if other special actions regarding the structural retrofitting of existing ones are also usually included. The issue that a structure has already been built, makes a difference in the application of the acceptable risk criteria and also difficult the leverage in setting the target performances among all exposed assets. Corrective measures are expensive and the development of structural retrofitting plans has a lot to do with who owns the exposed assets, bearing in mind that structural retrofitting schemes have followed usually a voluntary basis for private property and a mandatory one for essential public facilities such as hospitals, schools and administrative offices.

It has been concluded since long time ago that the associated cost of mitigating risk by means of structural retrofitting yields a significant potential benefit in terms of reducing potential damages and losses. Even if this premise has been largely debated and publicized, at least for private dwellings there are not yet enough incentives for a collective enrolment in those schemes. Some of the reasons are that owners have the belief that such extreme and infrequent events are not likely to happen to them and, also, that they do not see a short term return for the investment on structural retrofitting measures that can be expensive (these returns are in many cases the losses that did not occur and are therefore intangible). Among the benefits for a private owner to take retrofitting measures on the exposed asset is the decrease in the property insurance premium; nevertheless, under the pricing techniques that are used today, based on the law of large numbers that relate probabilities with frequencies, this can only be achieved if several dwellings, with the same structural characteristics and relatively close to each other, do the same. In other words, only one house among the complete portfolio cannot make any difference for such a reduction in the property insurance premium to take place. Still the debate on which is the best way to implement structural retrofitting schemes in terms of mandatory or voluntary basis goes on but, at this stage, it is also important to bring into the discussion the relevance of who is to decide whether or not those measures are necessary and acceptable, especially if those actions are included in a mandatory DRR framework.

The definition of an acceptable risk level also has consequences in what is to be classified as good or as bad. By setting an acceptable level, it can be then understood that any risks below that level can be ignored (Fischhoff, 1994), a characteristic which creates an additional question regarding for how long is to be considered a risk as acceptable. The concept of safety is dynamic in the sense that it evolves over time; what was considered as safe back in 1940 is not necessarily considered in the same way today (Spector, 1997). This makes also evident that independent of the chosen acceptable risk measure, said definition must allow new quantifications over the time and, additionally, be flexible during those updating processes (Cardona, 2001).

On the other hand, a society does not necessarily need a minimization of risks since there can be situations where, accepting the chance of having some losses, other objectives can be achieved (Renn, 1992). In those cases, it is still important to assess how those potential benefits obtained by risking something interact with other elements of the society and also what kind of legal and ethical liabilities they may pose, either explicitly or implicitly. An example for this is the case where an individual is the only owner of a building and decides to accept a high risk level during the design and construction phase because thus he will obtain some other financial benefits for his own. Even if assuming that the whole structure is to be later used and occupied only by the owner, in case of collapsing it will create a series of externalities with effects beyond what is normally assessed from the structural engineering perspective and with additional implications that those associated to the owners' wealth and heritage.

An example of the change with what is acceptable or not over the time has to do with wealth and income. Demand for safety increases together with both (Horwich, 1997; Toya and Skidmore, 2007) and it was found by Raschky (2008) that a 10% increase in the overall GDP is translated into an 8.7% reduction in mortality due to catastrophes of natural origin. This is not only seen in the human loss dimension but also in the monetary one since, as shown in the studies developed by Toya and Skidmore (2005; 2007), when an economy develops, both physical and human losses, when normalized by the GDP, are lower. Also, individuals with higher income implicitly or explicitly take expensive protection measures to respond to the new safety demand

(Schumacher and Strobl, 2011) and this is reflected in the disproportionate differences in the losses and casualties following earthquakes among the different income levels.

A paradox on what happens when increasing income and demand for safety occurs for people within the low-income category. They, by making some decisions and chasing some opportunities regarding the first, can decrease their safety against natural events by, for example, deciding where to live. A person looking for the incentive of accessing a better job that is available in a dense urban centre, may only find the way to do so by living within a hazard prone area and, therefore, increasing exposure and therefore the disaster risk level (Kellenberg and Mobarak, 2007). In this case, that person is making a decision that does not account for the risk minimization but for accepting some possible losses given that they represent a chance to obtain some other more tangible and immediate benefits. This example clearly shows that it is not enough to define an acceptable risk level only from the technical point of view but that also its pertinence, within a specific context is to be assessed. As mentioned before, minimizing risks may not be the best approach, not only because it can pose limitations in the development and search of different objectives and benefits that can be tangible and tradable at societal level, but also because the conditions to reach said level can be hard to meet, even more when most of the exposure already exists.

The performance objectives of the building codes for structures vary depending on their characteristics, mostly in terms of relevance and importance. While the three requirements mentioned at the beginning of this chapter apply to standard buildings (MAVDT, 2010), different and tougher ones are included for essential buildings, such as schools and hospitals, as well as for other non-building structures such as water storage tanks (AIS, 2013) and bridges (AIS, 2014). This choice highlights the fact that, in the decisions made so far regarding the acceptable risk in earthquake engineering, the societal benefit has always prevailed over the individual benefit.

The individual perspective of the acceptable risk is very different from the societal one (May, 2001) and, having mentioned this, it is also important to bear in mind that there are also cases where individuals do not choose necessarily what is best for them (Rosenblueth, 1976a). Recalling that seismic risk is as a public one for the reasons mentioned in Chapter 1 of this thesis, any decision made about it will unavoidably have consequences both at the individual and at the societal level. From the individual perspective, the collapse of a building may represent loss of wealth and heritage whereas from the societal perspective this same event will also have implications in terms of casualties, debris and its removal and other several community disruptions which need both human and monetary resources to be addressed. Even if assessed only in terms of costs, additional to the tangible damage there are other several indirect effects and among them, the cost of the structural collapse of a building has been established by Esteva (1970) as 10 times higher than that of the reconstruction, due to the loss of lives.

A clear advantage of clearly and explicitly defining an acceptable risk level is supported by the fact that once it has been set, a clear and transparent target is available to everyone; this is something essential for a proper disaster risk management. This, of course, needs to be complemented with the selection of appropriate metrics in which said level is expressed that, on the other hand, need to be useful at the same time, for review, enforcement and monitoring purposes. In all cases, the metrics need to be quantifiable, transparent and understandable besides being relevant and appropriate for what is being measured. These conditions about the metrics are mandatory independent on the selected acceptable risk level.

The definition of an acceptable risk level is not only a matter of adopting very strict requirements that minimize risks through the building codes, but on assessing the feasibility of their adoption and enforcement within a specific context. Building codes should only include requirements that can be enforced and that are appropriate where they are to be applied (Kleindorfer and Kunreuther, 1999). When the costs of buildings which comply with the earthquake resistant requirements are disproportionate if compared to other conditions of an economy, those documents are simply not used even if they have been widely discussed and correctly socialized within the community (Toya and Skidmore, 2005). Also, the adoption of a building code developed for an industrialized seismic prone country (e.g. Japan) in a low-income one (e.g. Haiti) will not be effective since most of the construction practices are not going to be familiar to local workers. Even if this last statement is not true, put in balance the decision on the allocation of monetary resources at the individual level for the construction of a safe structure with other actions that can yield immediate and tangible outcomes such as access to food and education; the second options are more likely to be chosen.

The costs of not having, adopting and enforcing an acceptable risk level are also to be considered. In the case of earthquakes, these are usually materialized in terms of physical damages and losses and in the aftermath of an event, one of the first questions that are raised has to do with who is to pay for them. Even in industrialized countries, the answer to this question is different and particular, ranging from cases such as in the USA where private property insurance is expected to be underwritten by the owners at individual level under a voluntary basis, to more egalitarian approaches such as the one existing in France, where risk is distributed among the totality of the citizens (Vallet, 2004). Whether a loss is to be paid by tax payers that collectively assist those affected after the occurrence of an event, by public and private insurance companies or by national, subnational and/or local governments which beforehand collect taxes for said purposes from residents and business owners who are located within hazard prone areas, is also a topic that can be better defined and addressed by setting a transparent acceptable risk level and clear performance goals.

What is too much risk (the question mentioned before) is a very subjective question and depends on the context. A risk may be acceptable for one but not for others (Ellingwood, 2001) and will depend, in the case of earthquake engineering at societal level on the answer to questions like the following:

- Should all losses be mitigated?
- What is the cost to adopt the proposed acceptable risk level?
- Should measures be developed even if the certain costs for reaching the acceptable risk level are higher than the possible potential savings in losses?
- Should an acceptable risk level be adopted even if it limits the development of other actions that can yield some other tangible benefits?

None of the above listed questions have a unique answer and a lot of thoughts are needed to be addressed in every case and, if it was only a matter of reducing the physical damage, the consideration of only technical criterion would be enough. Anyhow, since the consideration of intangible losses is also a critical part of these decisions, it becomes evident that a decision that requires a multidisciplinary approach is expected (Renn, 1992). It is not within the scope of this thesis to provide an answer to any of those questions but to present additional aspects for discussion when the decisions are to be made. Topics and aspects related to mortality have to be also considered, since they are relevant in this kind of assessments and decision-making processes (May, 2001) which goes in hand with the idea of Fischhoff (1983) on that what are to be defined are targets instead of requirements.

4.2 Who should decide?

Another topic which follows the discussion has to do with who has to decide what an acceptable risk level is. In the specific case of earthquake engineering, it is clear that for an appropriate decision making process, those involved in it need to have the adequate knowledge and understanding not only of the consequences but also of methodologies that can be used for the assessment. Therefore, the earthquake engineering field is one of those in which experts' criteria and opinions are required, accepting, beforehand, that what is to be defined by a collective of experts (e.g. national associations for earthquake engineering) is going to be applied to the society as a whole. Generally speaking, it has been seen that, when people recognize that they do not have the required knowledge about the risks with which they can be faced to, they tend to believe in the expert opinion and criteria (Renn, 2008).

On the one hand, individuals, if asked, do not want governments to make decisions of this kind for them but, on the other hand, most of individuals neither have the capacity nor the knowledge to make them. At individual, level the perception on low frequency events is highly distorted (Fischhoff, 1994) and it has been one of the biggest reasons to leave these kinds of decisions to experts who, of course, have a wider and more complete view on the topic. Earthquake engineering is a field where democracy cannot replace, at any stage, a scientific process; therefore the outcomes of the last are to prevail always, moreover in cases where the societal benefits have been preferred over the individual ones by the experts who have made the decisions. Experts appointed within a legal framework to make this kind of decisions need to make use of different tools and methodologies to assess risk and, therefore, define and legitimate its acceptance while, at the same time, those affected by the decision are only going to carefully follow those perceptions and interpretations about the consequences in order to avoid the risk (Renn, 2008).

The importance of defining who is to decide what an acceptable risk level is goes beyond the issue of granting making decisions. It has implications in for example defining who is to be held responsible if the selected criteria proves to be inadequate and, at the same time, limiting up to what point there is some responsibility of an individual (Renn, 2008). Coming again on the voluntary or mandatory basis for the development of structural retrofitting measures, in the case the second option is chosen and the acceptable risk level is defined by means of building codes, the decision on what is the acceptable level is to be made by experts (Starr, 1969).

The functions and objectives of a building code within a society are also issues that need to be considered and evaluated and, since long time ago, the debate about which should be the safety considerations they are to account for exist. Some engineer's opinions are on the side that these documents are to provide a set of requirements or targets aiming for minimum reliability aspects whereas for others the main objective is to derive in optimum designs, understanding by this those which maximize the utility and benefit to society (Rosenblueth, 1976b).

In the following section an example of an application of optimum design is developed for Colombia and is compared with the current building code requirements which go in hand with setting minimum reliability requirements, complementary to the ones listed at the beginning of this chapter.

4.3 Acceptable risk does exist in earthquake engineering

Although in many countries such as in Spain and Colombia the acceptable risk has not been explicitly addressed in the earthquake engineering field, it does not mean that it does not exist. In most seismic hazard prone countries, earthquake resistant building codes are available (even if their enforcement and application is not high or not even mandatory) and, as mentioned at the beginning of this chapter, they provide a set of minimum requirements with the aim of new structures reach a predefined performance target. Most building codes share a background philosophy of avoiding structural collapse and not explicitly include, neither mention, the protection of lives (Rosenblueth, 1976b; Liel and Deierlein, 2012).

The objective of earthquake engineering can be summarized as providing safe infrastructure in a way that a good use of the scarce resources is achieved. Designing and constructing a building totally safe against earthquakes is not a difficult task and by using extremely large beams and columns the no-damage objective can be easily met. Even if that building will have an excellent structural performance, it will result, without any doubts, in an unaffordable one for most of the citizens, even if leaving aside issues related to its limited practicality and functionality.

Additional to the resistance to gravitational loads, the design process of a structure requires the definition of the seismic forces that the building is expected to withstand and, for this purpose, probabilistic seismic hazard analysis is a common and acceptable practice. What has been used in several parts of the world is the selection of an acceptable exceedance probability, within a timeframe (usually associated to the lifetime of the structure) that, using equation 2.7, derives in a fixed mean return period. For buildings, this procedure has been performed by finding hazard intensities with exceedance probabilities ranging from 2, up to 10%, assuming a lifetime of 50 years[5].

Seismic hazard is non-linear and, in areas with high seismicity, important changes in the expected intensities can occur by the selection of one mean return period or of another. Additionally, the selection of a mean return period at national level does not guarantee that it is appropriate neither relevant for the complete territory, if important differences in the seismic activity exist. If only the safety considerations were to be taken into account, the selection of a high mean return period (i.e. 2,475 years) for all cases will make very expensive the design and construction of buildings and infrastructure in areas of high seismicity but, at the same time, the selection of an intermediate mean return period (i.e. 475 years) can leave aside the contribution to the seismic hazard of large and infrequent events in low seismicity areas.

Even if the fixed mean return period approach has performed well from the perspective of the reliability based design, the idea of using building codes as tools to optimize the benefits to society was introduced by Rosenblueth (1976b). This approach supports the idea that building codes should provide optimal design instead of minimum reliability requirements, leading to the use of seismic coefficients that optimize the benefit at societal level which, on the other hand, are not associated, at national level, with a fixed mean return period, leaving then aside the problems mentioned before.

Having said this, it is evident that the selection of an optimum strength level has a relationship with the capital investment used to guarantee the security of a building and that the mere results of a PSHA are not enough for that purpose. Countries like Mexico have used the optimum design approach for establishing the seismic design coefficients based on the above mentioned

[5] Corresponding to mean return periods of 2,475 and 475 years respectively

proposal (Pérez-Rocha and Ordaz, 2008; Tena-Colunga et al., 2009) and this methodology is explained in the following and results obtained for Colombia are shown. The estimation has been made using the *optimum spectra* tool of the seismic hazard analysis program CRISIS2015 (Ordaz et al., 2015).

Together with the idea of the optimum design go in hand the benefits of what the risk acceptance has associated (May, 2001) and, in the light of this, the optimum design approach explicitly accounts for the economic factors involved during the construction and life-service time of a building. This is done by selecting the seismic coefficient value that minimizes the initial construction cost, C_I as well as the cost of the future losses due to earthquakes, C_{FL}. Thus, the total cost of the structure C_T is estimated as

$$C_T = C_I + C_{FL} \qquad (4.1)$$

Since all the costs are a function of the seismic design coefficient, c, they can be denoted as $C_I(c)$, $C_{FL}(c)$ and $C_T(c)$ and then, Equation 4.1 can also be rewritten as

$$C_T(c) = C_I(c) + C_{FL}(c) \qquad (4.2)$$

If the building was to be designed only to withstand gravitational loads, there would still be a cost associated to that objective, in this case denoted as C_0. That same building will also have a lateral strength which, when using this methodology is assumed to be free of charge and denoted as c_0. The initial cost of the structure can be then calculated as

$$C_I(c) = C_0 + C_{Res}(c - c_0)^{\alpha} \qquad (4.3)$$

where C_{Res} is the cost of the planned and paid lateral resistance, and α is a parameter that considers the cost increase of the structure with an increasing seismic design coefficient.

If Equation 4.3 is normalized by C_0, it can be rewritten as

$$\frac{C_I(c)}{C_0} = 1 + \frac{C_{Res}}{C_0}(c - c_0)^{\alpha} \qquad (4.4)$$

and, if the ratio between C_{Res} and C_0 is denoted as ε, Equation 4.4 finally becomes

$$\frac{C_I(c)}{C_0} = 1 + \varepsilon(c - c_0)^{\alpha} \qquad (4.5)$$

In this methodology, it is assumed that $c \geq c_0$ since c_0 is generally very little. It is also important to bear in mind that c_0 depends on the fundamental period and, for longer ones, the free of charge lateral resistance may be lower.

The net present value of the future losses due to earthquakes, $NPV_{FL}(c)$, needs to be considered and, again, it is assumed to be a function of the seismic coefficient. $NPV_{FL}(c)$ can be calculated as

$$NPV_{FL}(c) = C_I(c) \cdot (1+S_L) \cdot \frac{\nu(c)}{\mu} \tag{4.6}$$

where S_L is a parameter that accounts for secondary losses and human losses, $\nu(c)$ is the exceedance rate of the seismic demand, obtained directly from the PSHA and μ is the discount rate to consider the value of money in the future. The mean return period variable is truncated to minimum and maximum values, T_{Min} and T_{Max}. The first one is according to the building code philosophy of establishing minimum requirements while the second one is used to avoid accelerations associated to not plausible earthquakes in areas of very low seismic activity.

With this, the estimated design coefficient is explicitly associated to an optimum economic solution in which the benefits of using that safety level are presented to all users in a transparent way.

From the PSHA developed for Colombia, whose details can be found in Annex 1 of this thesis, the uniform hazard spectra (UHS) shown in Figure 4-1 for different capital cities, and for 475 years mean return period were obtained. It is worth noting that the PSHA has been performed at bedrock level.

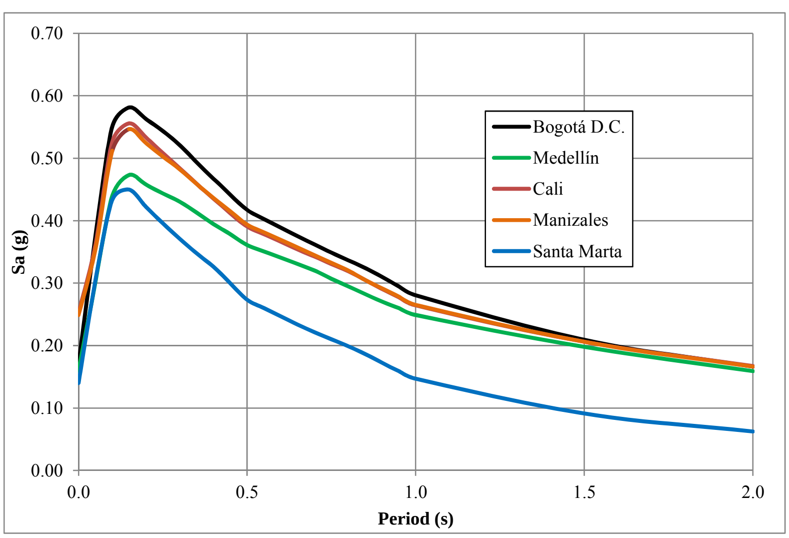


Figure 4-1 UHS for different cities in Colombia (475 years mean return period)

From the UHS it can be seen that the period corresponding to the highest spectral accelerations at bedrock level of Colombia, and according to the GMPEs used, are around 0.15s (Bernal, 2014). With this in mind, a cost model based on a function of the seismic design coefficient is developed for the low-rise reinforced concrete frame building class, whose fundamental period has a similar value.

For the estimation of the equivalent seismic forces the elastic design spectra of the Colombian earthquake resistant building code, NSR-10 (MAVDT, 2010) - and shown in Figure 4-2 - was used for soil type B and assuming A_a=A_v. Because of the characteristics of the analysed building, the structural design was made according to the requirements of the IPS-1 document of the American Concrete Institute (AIS et al., 2003).

The NSR-10's elastic design spectra is defined by seismic design coefficients at short and intermediate periods, A_a and A_v respectively, the soil amplification factors F_a and Fv associated to the soil conditions and a importance factor, I.

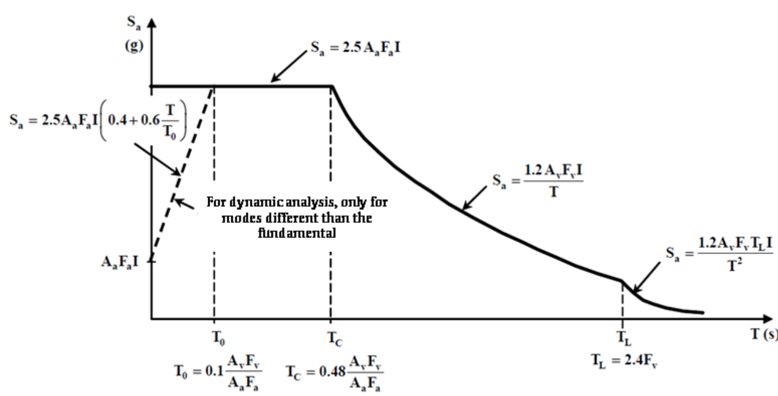


Figure 4-2 Elastic design spectra for Colombia according to NSR-10 (from: MAVDT, 2010)

The variation of $C_I(c)$ is calculated for 0.05g steps using values corresponding to local construction material and also by reviewing previous studies developed in the country on this topic (García, 1993; 1996) from where the ε and α parameters are established in 0.022 and 1.32 respectively. Figure 4-3 shows the initial cost function defined by equation 4.5 using the values mentioned above for the parameters ε and α.

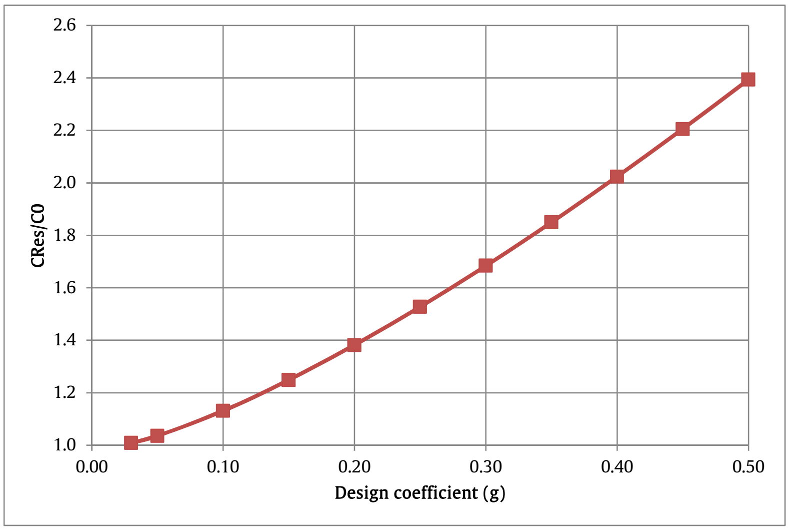


Figure 4-3 Initial cost as a function of the design coefficient

For this case it has been assumed that c_0 is equal to 3% of g (29.43cm/s^2) while a value equal to 12 has been used for the parameter S_L, following the recommendations of Ordaz et al. (1989). Finally, a discount rate, *μ,* of 4% is used considering the historical and projected economic behaviour of Colombia. Finally, T_{Min} and T_{Max} have been established in 250 and 2,500 years respectively. With these data, the optimum spectral ordinate corresponding to a period of 0.15s are obtained and divided by a factor of 2.5 to obtain the optimum design coefficients in terms of PGA, which are shown in Figure 4-4. The hazard values transition between adjacent locations is smoother than the ones obtained for fixed mean return periods such as the ones developed by AIS (2010; 2013) and Salgado-Gálvez et al. (2010; 2015c).

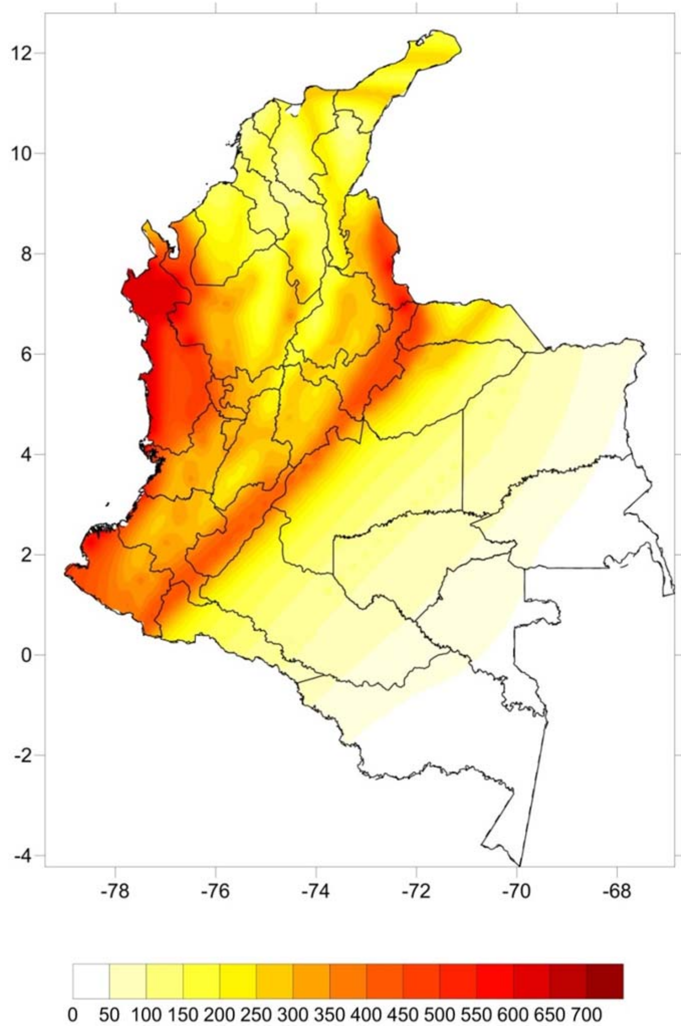


Figure 4-4 Optimum PGA values for Colombia (cm/s^2)

For the fixed mean return period approach, PGA has been established according to AIS (2010) and MAVDT (2010) in 0.15g for Bogotá D.C., Medellín and Santa Marta whereas for Cali and Manizales for 475 years mean return period[6] it was 0.25g. Those results, if compared to the ones obtained in this study, show an increase to 0.27g for Bogotá, 0.26g for Medellín, 0.28g for Cali, 0.28g for Manizales and 0.26g for Santa Marta, as shown in Figure 4-5. These increases in the seismic design coefficients can be interpreted, under this approach, as earthquake safety which was cheap to buy but that has been not bought, leading

[6] These values were rounded to 0.05g after the initial PSHA

to structural designs that provide structures with costs far apart from the optimum solution.

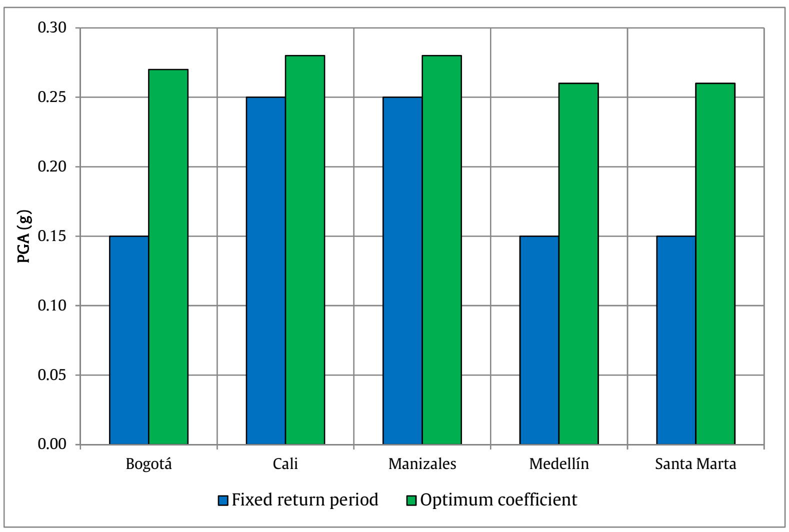


Figure 4-5 Comparison of seismic coefficients for 5 cities in Colombia. Fixed mean return period and optimum design approaches

If the optimum approach was to be adopted in the building code, a revision of the elastic design functional form can be needed given the differences in the way the seismic coefficients are being established. Figure 4-6 shows the comparison of the elastic design spectra for Bogotá using the design coefficients established in the NSR-10 (AIS, 2010; MAVDT, 2010) and the ones obtained after applying the optimum design methodology presented herein. For consistency, and since the estimation of the optimum accelerations has been done for a single spectral ordinate, it has been assumed that the optimum acceleration is equal for both, A_a and A_v parameters. Soil type B has been chosen and that means that Fa=Fv=1.0. A significant increase exists in the short and mid-range of fundamental periods.

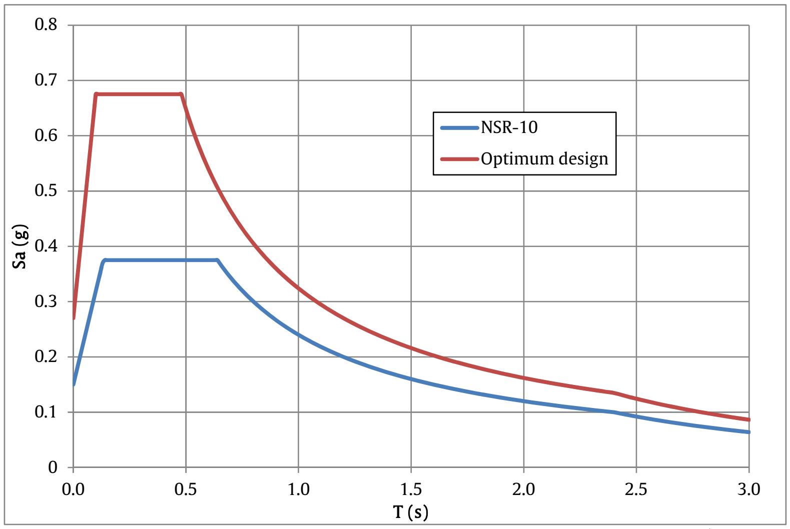


Figure 4-6 Comparison of elastic design spectra for Bogotá

Once the value of *c* is established at the different locations, it is also possible to obtain from the hazard curves its associated annual exceedance rate and finally estimate the mean return period associated to the optimum design coefficient. This, of course, and as mentioned before, leads to different mean return periods at each calculation point and, under this framework, lower mean return periods are expected in areas of high seismicity whereas longer ones are expected in areas of low seismic activity. This last observation shows that it is very cheap to buy earthquake safety even if associated to high mean return periods in those areas.

Figure 4-7 shows the geographical distribution of the mean return periods associated to the optimum design coefficients established for Colombia. The lowest values occur in the Pacific Coast, with mean return periods of approximately 300 years, whereas for the areas of low seismicity, the T_{max} value applies.

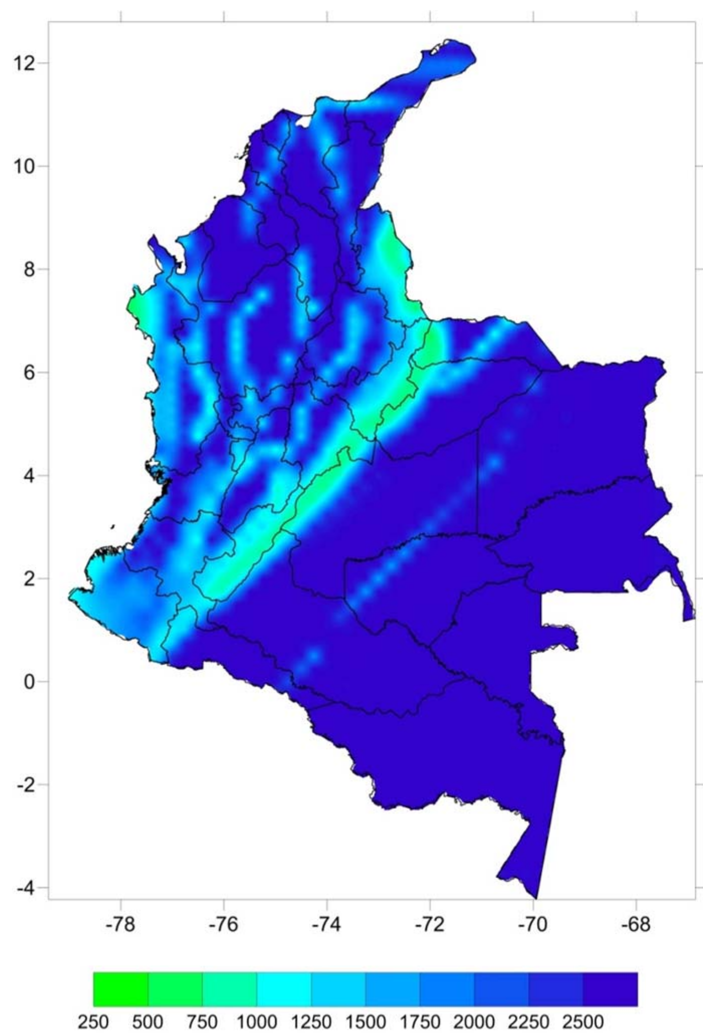


Figure 4-7 Mean return period for the optimum design coefficients in Colombia (years)

If these values of the seismic design coefficients were to be used within the earthquake resistant building code, risk acceptance would be on the side of the invested capital for the construction of the building and not on the side of the frequency of occurrence. Under this approach, depending on the location of the building and on the seismic activity of the area, earthquake forces with different frequencies can be assumed as acceptable and the solution at national level can be considered as optimal since it maximizes the societal benefits of the construction and the cost of future losses.

For the purpose of helping and making easier the enforcement of building codes, the territory under analysis is usually divided into areas with homogeneous seismic hazard level. Even if it is still possible to develop this task with the results obtained with this methodology, it is also true that most of the available geographical information systems (GIS) allow the definition, verification and enforcement of the defined seismic design coefficients at any location.

The results obtained under the optimum design approach are not to be confused with those obtained after choosing a target performance, in terms of structural collapse and hazard intensities (accelerations) that lead to a uniform annual collapse probability. This last procedure is known as risk-based hazard maps (Luco et al., 2007) and was first developed for the USA and implemented into the building code requirements from 2007. The idea was that consistent safety levels go in hand with uniform and also understandable risk metrics (Luco et al., 2007; Liel and Deierlein, 2012), mentioned at the beginning of this chapter.

Under that approach, both total and annual collapse probabilities can be estimated also making use of the results of a PSHA. The total collapse probability can be estimated as (Hadjian, 2002)

$$P_F = \int_0^\infty F(a) \cdot h(a) da \tag{4.7}$$

where $F(a)$ is the fragility distribution (normally represented by a lognormal one), $h(a)$ is the probability density function for the median of the hazard intensity and a is the seismic hazard intensity measure. Now, if what is to be assessed is the annual collapse probability, it can be estimated as

$$P_{collapse} = \int_0^\infty P(Sa > a) \cdot f_{capacity}(c) dc \tag{4.8}$$

where $P(Sa>a)$ is the annual exceedance probability of the intensity a and $f_{capacity}(c)$ is the fragility function commonly expressed by means of a lognormal distribution.

This approach highlights the impact of structural uncertainties upon the seismic risk. If it was negligible or equal to zero, the uniform hazard approach would undoubtedly lead to a uniform risk result. This is not the case when the uncertainty associated to the structural response is considered and, therefore, the collapse probabilities associated to a fixed mean return period for the hazard are not the same. It is also important to mention that the percentile value chosen for the fragility representation by means of a lognormal distribution also has an important role in the assessment, showing also that physical vulnerability is the most sensible parameter when estimating seismic risk (Crowley and Bommer, 2006).

Under this approach, a target (or acceptable risk) annual collapse probability is fixed by experts and it can range between $1x10^{-5}$/year (Rosenblueth, 1976b; Douglas et al., 2013), to $2x10^{-4}$/year[7] (Luco et al., 2007) and once it is defined, an iterative process to calculate the seismic intensity measure (usually PGA) associated to that fixed annual collapse probability at each point is necessary. If desired, the mean return period associated to said PGA value can be obtained, leading again to a different value at each location.

This approach has the advantage, in the opinion of some authors (Luco et al., 2007; Liel and Deierlein, 2012; Douglas et al., 2013), that by explicitly defining a performance goal (i.e. the collapse probability) it is easier to define whether the building comply with the requirements or not.

Finally, it is worth mentioning that the definition and use of seismic design coefficients obtained under any of the above mentioned two methodologies, would only be applicable for new buildings and that special measures would be needed for structural interventions in the existing assets.

[7] Dikes in the Netherlands are designed for an annual probability of water exceeding the design level equal to $1x10^{-4}$ (Woo, 2011)

Chapter 5

AVERAGE ANNUAL LOST ECONOMIC PRODUCTION DUE TO PREMATURE LOSS OF LIVES

5.1 Introduction

This chapter presents the proposal for the probabilistic and prospective estimation of the annual lost economic production due to premature loss of lives because of earthquakes. This annual lost production can be understood as the annual lost collective contribution to GDP and, therefore, pursuing an answer for what is the amount that society should be willing to spend in order to protect loss of lives against earthquakes, can provide an order of magnitude on what the minimum investment for said purpose, in terms of corrective measures, should be. The results obtained with the proposed methodology allow addressing an issue first introduced by Rosenblueth (1976a) about the costs of saving lives who states that society must be willing to spend the present value of the average contribution of the individual to the GDP during the rest of his/her life.

The aim of the methodology is to provide a framework in which, using a linear relationship between annual investment on seismic safety and lifesaving, other dimensions of loss different than the physical ones are considered in a probabilistic way. These monetary amounts have to be understood as the minimum public investment on seismic safety to be materialized in corrective measures (e.g. structural retrofitting), a process which shall start by intervening the public infrastructure. This quantification not only allows for a technical based allocation of resources in seismic areas but also for raising risk awareness and promote interventions in areas with low historical seismicity where, because of that, high physical vulnerability levels exist which can induce important losses in both human and physical dimensions.

In the public health field, the disability adjusted life year (*DALY*) is a commonly used metric developed in the 1990's as a measure of disease burden for comparison of overall health and life expectancy in different countries. 1 *DALY* corresponds to 1 lost year of healthy life. According to the methodology proposed by the World Health Organization in the latest release of the global burden of disease (WHO, 2013) it can be estimated by adding two components as follows:

$$DALY = YLD + YLL \tag{5.1}$$

The first, *YLD*, is the adjusted number of years lived with disability and the second, *YLL,* is the number of years of life-lost due to premature mortality. *YLL* is calculated as the number of deaths multiplied by the life expectancy at the age of death. The estimation of that metric is based mostly on historical data and, therefore, can be classified as a retrospective one. Altogether, *DALY* is calculated as the sum of the number of adjusted life years with disability and the number of life-lost years due to premature mortality (Larson, 2013; WHO, 2013; Devleesschauwer et al., 2014).

Based on one of the ideas behind the *DALY*, the estimation of the average number of years of lost-life due to premature mortality because of earthquakes, *YLL*, is proposed herein. *YLL* consider only those deaths associated to building collapse by using probabilistic CAT-models instead of historical data, being thus a prospective and probabilistic metric. The methodology uses the same conceptual framework as the CAT-models explained in Chapter 2 and the same requirements for input data, together with the assumptions, scope and limitations still apply.

Regarding *YLD*, although with state-of-the-art CAT-models it is possible to estimate the expected number of injured by earthquakes, it is not yet possible to accurately make estimations of the kind of injuries and, therefore, the time either to remission or death. Because of that, *YLD* due to earthquakes cannot be estimated in a prospective way and, therefore, it is not included in the estimation of lost production proposed in this thesis.

5.2 Assumptions, scope and required data

Premature mortality has been on a constant reducing process for the case of diseases as a consequence of the development and implementation of technological and medical knowledge. Earthquakes pose a demand to buildings, even if for only a reduced quantity of seconds, to withstand their forces. Still, to make this happen, it is a challenging task for engineers and builders despite of today's understanding on the phenomena, which at the same time has allowed developing appropriate earthquake resistant building codes with the objective of avoiding structural collapse, saving then hundreds and even thousands of lives.

In order to present in a transparent way the scope and limitations of the proposed methodology, the following main assumptions have to be taken into account:

- Hazard is considered to be stationary.

- Exposure and vulnerability are characterized based on today's conditions.
- Since human occupancy is a dynamic exposure parameter, different occupation levels can be assumed. Several formulations that consider time, day and season issues are available and can be used. Considering a full occupation of the buildings is not recommended and care must be taken to avoid double counting of occupants.
- Only indoor fatalities associated to the collapse of buildings and houses due to of earthquakes are considered.
- Age is not considered to be a characteristic that makes any difference for lethality ratios in the case of building collapse because of earthquakes.
- The lost economic production only considers the working-age group which, on the other hand, is assumed to be that defined by the OECD (15-64 years).

The proposed methodology has the following scope:

- Estimate, within a probabilistic framework, the average annual deaths *AAD* due to building collapse.
- Combine the *AAD* overall results with demographic data to estimate the average annual number of life-lost years.
- Using the GDP per capita as a macroeconomic indicator, estimate the associated cost in terms of lost economic productivity of the premature deaths at different resolution levels.
- The obtained monetary value should be understood as a reference for what should be the minimum public investment in corrective measures regarding seismic safety.

The proposed methodology requires information about the following issues:

- Hazard: the proposed methodology can be applied for different natural hazards, although the scope of this thesis only covers the seismic one. This input can be delivered in terms of any of the following representations:
    - set of stochastic events,
    - hazard curves.

  The event-based representation is used in all cases.
- Building classes: since casualties are related to the characteristics of the buildings, the differentiation of buildings into typologies is required.
- Lethality ratios for each identified building class.
- Human exposure: for each entry on the exposure database, the expected number of exposed people is required. Although this is a

dynamic parameter (people move around depending on time, day and season), different methodologies to define this value exist. The total value is truncated to the number of inhabitants of a region and neither migration nor tourist behaviour is captured.

- Vulnerability: for each considered hazard and building class, a function that relates the expected *MDR* and *LR* with the hazard intensity is required.
- Life expectancy at birth: this value is required for the moment at which the analysis is being performed. In some countries there may be important variations for the same parameter depending on the region and therefore, several values can be considered in sub-national assessments or a weighted average can be used.
- Population age distribution: the age distribution for the population under consideration is needed, which is usually found in 5 to 10 years ranges.
- Gross domestic product per capita: GDP per capita is later used to convert the number of productive life-lost years into lost economic production. As in the case of the life expectancy at birth, this value can vary among regions within the same country and again, different values or an overall figure can be used.

Different case studies developed with three spatial resolution levels are included at the end of this chapter as an application of the proposed methodology.

5.3 Methodology

The proposed methodology is based on the most robust probabilistic risk metric, the average annual loss (*AAL*) (Marulanda, 2013; Niño et al., 2015) which was described in Chapter 2 and that can be calculated using the following equation:

$$AAL = \sum_{i=1}^{N} \mathrm{E}(L|Event_i) \cdot F_A(Event_i) \tag{5.2}$$

where $\mathrm{E}(L|Event_i)$ is the expected loss value given the occurrence of the i^{th} event and $F_A(Event_i)$ is the associated annual occurrence frequency of the same event. This approach requires a stochastic event set which needs to fulfil the requirements of being collectively exhaustive, mutually exclusive, be described by at least the first two probability moments and account for the temporal and spatial randomness. Nevertheless, in some cases, seismic hazard information is not available in that representation but in terms of intensity exceedance curves (also known as hazard curves) which, in the case of earthquakes, usually relate acceleration levels with their corresponding annual exceedance rates. Based on that information, it is also possible to calculate the *AAL* by using the following expression:

$$AAL = \sum_{i=1}^{EA} \int_0^{\infty} -\frac{d\nu(a)}{da} \cdot E(l \mid a)_i \cdot da \qquad (5.3)$$

In this case $\nu(a)$ is the annual hazard intensity exceedance rate, *EA* is the total number of exposed assets, *a* is the hazard intensity and $E(l|a)$ is the expected value of the loss given a hazard intensity a in the i^{th} exposed element. If PSHA has been performed in a rigorous and exhaustive way, the use of equation 5.2 or 5.3, leads to the same value of *AAL*. Among the probabilistic risk metrics, it has been studied that the hazard and vulnerability uncertainties and their variations have more impact in the *LEC* than in the *AAL* (Crowley and Bommer, 2006).

The input that needs to be specified within a probabilistic risk assessment framework to obtain the loss in terms of its different dimensions are the vulnerability functions, which, as previously explained, relate the expected hazard intensities to the expected losses. Different efforts for their development have been made at global level, such as those mentioned in Chapter 2, in order to establish relationships that allow estimating casualties, both in terms of injured and deaths, associated to earthquakes (Coburn and Spence, 2002; FEMA, 2003; Spence and So, 2009; Jaiswal and Wald, 2010; Jaiswal et al., 2011). They all can be classified as empirical since they are mostly based on post-earthquake surveys.

The proposed methodology can be applied considering other hazards with natural or anthropogenic origin as long as the vulnerability functions that allow estimating the associated deaths can be developed and the hazard representation also allows estimating *AAL* (i.e. a single mean return period hazard map is not suitable for that purpose). The methodology can be applied at different resolution levels providing an opportunity to estimate the minimum public investment on seismic safety to reduce mortality due to earthquakes at country, subnational and urban level, providing information that can be useful to different stakeholders and decision-makers depending on the legal and administrative organization regarding allocation of public resources in the area under analysis.

Estimation of deaths caused by the collapse of buildings during an earthquake using state-of-the-art CAT-models still constitutes a big challenge (Ferreira et al., 2011). It is not only because population data to be included in the exposure databases are a dynamic parameter that depends on the day, time and even season but, also, because the existing casualties' consequences databases provide limited information; therefore it is difficult to develop robust and reliable human vulnerability functions. The number of deaths estimated with this methodology and the vulnerability functions developed herein only consider buildings that collapse as an immediate consequence of the earthquakes and not due to secondary hazards like tsunami, landslides and fires that may be triggered by them. Acknowledging that there can be also deaths by causes different than seismic building collapse, it has been established that around 90% of the deaths during past earthquakes around the world have been caused by structural collapse (Coburn and Spence, 2002), a figure that is assumed to be statistically significant and, thus, usable for the estimation of the annual lost production due to premature mortality.

The first input to the methodology is the *AAD*, a metric that is based on the same basis and assumptions than the *AAL*, that is, it considers the participation of all plausible earthquakes, an infinite timeframe for their occurrence is assumed, damaged structures are rebuilt or repaired to the initial conditions after they have been damaged, and in this case, the same human occupation level remains after the structure is repaired.

Analogously to the *AAL* (Equation 5.2), the *AAD* can be estimated directly when using an event-based seismic risk assessment

$$AAD = \sum_{i=1}^{N} E(\mathrm{D} \mid Event_i) \cdot F_A(Event_i) \qquad (5.4)$$

where N is the total number of representative seismic hazard events, $F_A(Event_i)$ is the annual frequency of occurrence of the i^{th} hazard event and $E(\mathrm{D}/Event_i)$ are the expected deaths because of collapse of the exposed assets given that the i^{th} event occurred. In the cases where no stochastic representation for the seismic hazard is available, Equation 5.3 can be used considering the human deaths dimension when estimating loss. Since occupancy is a dynamic parameter and, neither its daily or seasonal variations can be well established, average occupancy rates like the ones proposed by FEMA (2003), Mistrani-Reiser (2007) and Liel and Deierlein (2012) can be used.

If *AAD* is calculated for other hazards, it can be added arithmetically since it corresponds to an expected value. This allows implementing the proposed methodology in multi-hazard risk assessments, suitable for areas where more than one hazard, with different origin, can cause significant consequences to its inhabitants and, therefore, additional investments to cover safety against them are needed.

Based on censual data, it is usually possible to establish the age distribution of the inhabitants in the area under analysis. Usually, data are grouped into age ranges of 5 to 10 years spans and are updated on a regular basis. The age distributions to be used in the proposed methodology correspond to the updated at the moment of the analysis. Assuming that there are M age ranges, the population distribution can be estimated for each of them and is denoted herein as P_r. The age distribution is based on the demographic statistics and is assumed to be the same for the whole area of analysis. Since all the inhabitants fall only into one and only one of the age ranges, the following condition is always met:

$$\sum_{n=1}^{M} P_r = 1.0 \quad (5.5)$$

It may be argued that the age distribution in a society varies over time but, again, in order to be consistent with the risk analysis framework used herein, what it is intended to be captured are today's conditions and characteristics and, therefore, what is being assessed are todays' risk levels.

Based on the P_r, and having previously calculated the *AAD*, it is possible to estimate the AAD_i which corresponds to the *AAD* by age range, obtained by multiplying the total *AAD* by its correspondent P_r factor. This step assumes that the age distribution of the deaths because of earthquakes have the same characteristics as that for the base population, which can be considered an appropriate assumption in the case of earthquakes since, for the type of injuries that cause deaths in those cases, the age factor does not constitute a differential cause. Therefore, in all cases

$$\sum_{i=1}^{M} AAD_i = AAD \quad (5.6)$$

Life expectancy at birth is a value that usually is available from official sources given its importance in different social, security, economic and public health aspects. A single value for it is needed in the proposed methodology for the area under analysis, reason why, if the available information is disaggregated by, for example, gender or smaller geographical units, a weighted average can be calculated and later used. Unitary years of lost-life because any cause by age ranges (L_i) are obtained by calculating the difference between the life expectancy at birth and the mean value of the age range (e.g. if the age range is 20-24 years, its mean value is 22.5 years). With this, it is being assumed that years within each age range are uniformly distributed. Life expectancy at birth at the moment of the analysis is to be used again to be consistent with the probabilistic risk assessment framework. Some frameworks use a global average value of 92 years (WHO, 2013), considerably higher than most of the 2015 life expectancy at birth values, mainly in developing countries.

By multiplying L_i by AAD_i, the YLL_i are obtained corresponding thus to the average annual number of life-lost years due to premature mortality because of earthquakes by age range. Since this is an expected value, it can be arithmetically added and the sum of the YYL_i of the *M* age ranges corresponds to the overall average annual number of years of life-lost due to premature mortality for the area under analysis, *YLL*

$$YLL = \sum_{i=1}^{M} YLL_i \quad (5.7)$$

To relate the average annual number of life-lost years due to premature mortality because of earthquakes with its consequences on production, the gross domestic product per capita is used. As explained in Chapter 3, GDP is the economic index that best measures economic welfare. Due to the characteristics of an economy, it can represent both, the income of all the members of an economy or the total expenditure in the production of goods and services on it. Disability-adjusted life years *(DALYs)* estimations in some cases have applied what is known as social weighting (WHO, 2004), that is, appraising the years according to the age based on the fact that it is on the working-age range that the peak productivity exists for each individual. In this thesis, the estimation of the lost productivity only considers the YLL_i associated to the employed working-age population which, according to the Organization for Economic Co-operation and Development (OECD), is constituted by those aged 15 to 64 (OECD, 2014). Within that range, all years are considered to contribute equally to productivity. Therefore, the average annual lost productivity due to premature mortality because of earthquakes ($AALP_{YLL}$) is estimated by means of

$$AALP_{YLL} = YLL_{(15-64)} \cdot GDP_{/\text{capita}} \tag{5.8}$$

It is important to remember that the same assumptions made for the calculation of *AAL* apply to the $AALP_{YLL}$ from where the most important at the moment of interpreting the results is that the estimated cost represents an average value which, in the long term, represents the annualized cost in terms of lost productivity due to premature deaths by future earthquakes with different magnitudes, locations and characteristics. Now, this value, seen as the minimum public investment in seismic safety by means of corrective actions, is to be understood as the resources required to gradually to decrease mortality because of earthquakes following the egalitarian ethical premise that saving a life is independent of the life saved.

Both *AAD* and $AALP_{YLL}$ are relevant risk metrics that cover a dimension which, so far, has not been explicitly addressed neither in a probabilistic nor in a prospective way. In probabilistic risk assessments only direct losses associated to physical damages of the built stock are obtained and, in some cases, used as a basis for the estimation of variations in economic flows that account for the indirect losses. None of them account for the expected lost productivity due to premature mortality and how this is linked with the amount of what should be the minimum public resources to be spent on corrective measures with the aim of reducing mortality because of earthquakes.

The proposed methodology has some limitations that are important to be highlighted with the objective of promoting future research that may contribute to improvements. First, only the life-years lost due to premature mortality are considered herein and it would be desirable to be able to estimate *YLD* and assess its impact in terms not only of lost productivity but also on medical expenses. Second, deaths associated to other damage states different than collapse and occurring outdoors, although being a small fraction, are not considered for this lost productivity assessment.

5.4 Physical to human vulnerability functions

As mentioned before, vulnerability has several dimensions (Carreño et al., 2007; Marulanda et al., 2009) and the methodology proposed in this thesis embraces the physical and the human ones. More specifically, *MDR* and *LR* (for indoor fatalities produced by building collapse) are to be estimated for the objectives of this thesis and, for the last, human vulnerability functions need to be developed. Vulnerability functions describe the variation of the loss probability moments as a function of the seismic demand as shown in Figure 5-1 for the case of medium-rise reinforced concrete buildings designed for low code level.

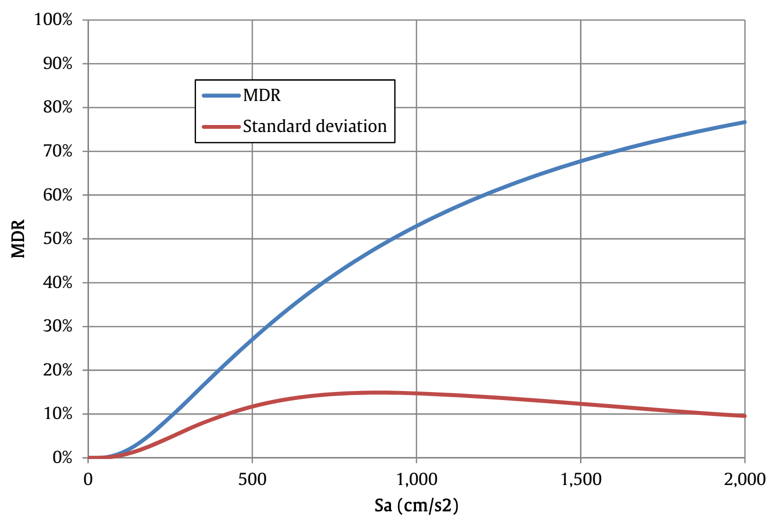


Figure 5-1 Physical vulnerability function for medium rise reinforced concrete dwellings

The loss L is defined as a random variable and the variation of its probability moments for different seismic demand levels are described by means of vulnerability functions. The loss probability distribution $p_{L|S}(L)$ is assumed to be a Beta function (ATC, 1985) where then, the first two probability moments correspond to the mean (*MDR*) and its standard deviation

$$p_{L|S}(L) = \frac{\Gamma(a+b)}{\Gamma(a)\cdot\Gamma(b)} L^{a-1}(1-L)^{b-1} \qquad (5.9)$$

where Γ is the Gamma function and the parameters a and b are

$$a = \frac{1 - (1 + c^2(L \mid S)) \cdot E(L \mid S)}{c^2(L \mid S)} \tag{5.10}$$

$$b = a \cdot \frac{1 - E(L \mid S)}{E(L \mid S)} \tag{5.11}$$

E(L|S) is the expected loss value and *c(L|S)* is the coefficient of variation of the loss given a seismic demand *S* which is obtained by dividing the mean value by the standard deviation

$$\mathrm{c}(L \mid S) = \frac{\sqrt{\sigma_L^2(L \mid Sd(T_s))}}{E(L \mid Sd(T_s))} \tag{5.12}$$

where $\sigma_L^2(L|Sd(T_s))$ is the variance of the loss at any spectral displacement, a value that is calculated adopting the damage probability distribution from ATC-13 (1985)

$$\sigma_L^2(L \mid Sd(T_s)) = Q(E(L \mid Sd(T_s)))^{r-1}(1 - E(L \mid Sd(T_s)))^{s-1} \tag{5.13}$$

where Q and s can be calculated as follows:

$$Q = \frac{V_{\max}}{L_M^{r-1}(1 - L_M)^{s-1}} \tag{5.14}$$

$$s = \frac{r-1}{L_M} - r + 2 \tag{5.15}$$

$V_{\max}$ is the maximum loss variance between 0 and 1, L_M is the loss where the maximum variance occurs and r is a shape factor. With this, once the expected loss value and its variance are established, it is possible to estimate the probability distribution given any spectral acceleration.

Human vulnerability functions are not available in the GAR15 vulnerability datasets but can be derived from the available physical vulnerability functions using the procedure proposed by Bernal (2015) using the following equation

$$\Pr(L > L_c) = \int_{L_c}^{1} f(L) \cdot dL \tag{5.16}$$

where L is the loss, L_C is the loss associated to collapse (the fixed *MDR*) and $f(L)$ is the probability density function of the loss. For this, the parameters a and b are calculated for each *Sa* and for each physical vulnerability function using equations 5.10 and 5.11 respectively. By setting a *MDR* that represents the possibility for the beginning of structural collapse (not necessarily 100%) the probability of reaching that damage state for different ground motion intensity values is obtained. The hazard intensity measure remains the same in both physical and human vulnerability functions, that is, *Sa* as shown in Figure 5-2 where a *MDR* equal to 0.55 has been set for the medium-rise reinforced concrete dwellings.

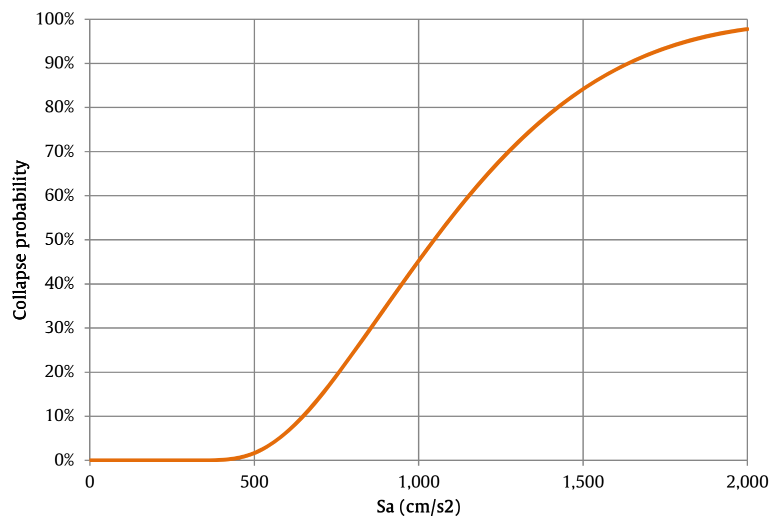


Figure 5-2 Collapse probability function for medium rise reinforced concrete dwellings

After this, a *LR* based on previous studies (Coburn and Spence, 2002; FEMA, 2003; Spence and So, 2009; Jaiswal and Wald, 2010; Jaiswal et al., 2011) for indoor fatalities associated to the collapse of building is assigned to each building class (the one used in this example is 10%); the expected deaths number is obtained as a fraction of the total number of occupants, for different *Sa* and for each building class as shown in Figure 5-3. This approach has been considered more convenient than the previous functions based on macroseismic intensity such as the Modified Mercalli Intensity (*MMI*) (see Chapter 2).

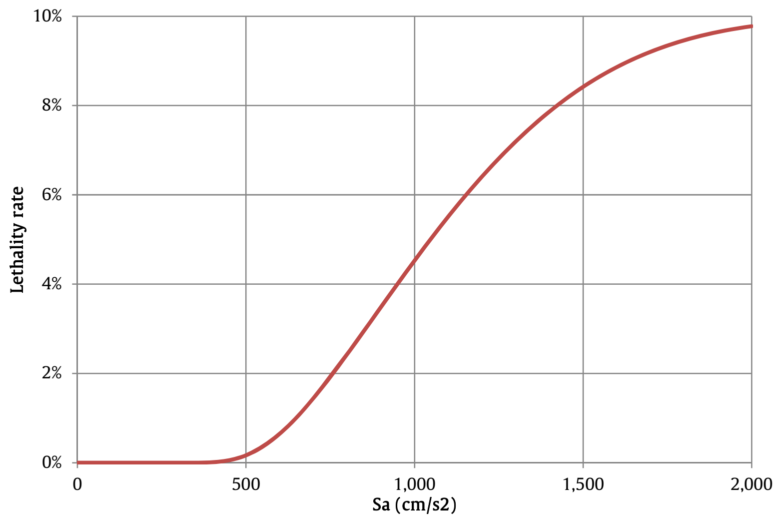


Figure 5-3 Human vulnerability function for medium rise reinforced concrete dwellings

Following the same procedure, changing *MDR* and *LR* for the considered building classes, a set of human vulnerability functions was derived. It is worth noting that, since the chosen risk metric is based on the expected value, by defining only the expected loss value in the human vulnerability functions the results can be obtained. Annex 2 presents the plots of the physical and human vulnerability functions obtained in this thesis, as well as the assumed collapse *MDR* and associated *LR*.

5.5 Application of the methodology at country level

For the Latin America and the Caribbean (LAC) region as well as for Spain, the employed seismic hazard model corresponds to that developed by CIMNE and Ingeniar (2015) at global level using a probabilistic approach, based on smoothed seismicity and a seismo-tectonic regionalization which details can be found in Annex 1. The exposure database corresponds to that developed under the GAR15 framework (UNISDR, 2015a) at 5x5km resolution level by De Bono and Chatenoux (2015). The exposure database covers both urban and rural areas and each entry has information about the development and complexity levels, building classes and human and capital exposed values. The physical vulnerability functions correspond to the ones developed by CIMNE and Ingeniar (2015) for this same project and from them, using the lethality ratios proposed by FEMA (2003) and Jaiswal et al. (2011) the human vulnerability functions were derived. Data for life expectancy at birth, projected population to 2015 and distribution of it in 5-years age ranges was obtained from the UN Population

Division (2015) for each country. In all cases a 60% occupation level has been assumed.

Countries with different characteristics in terms of seismic hazard, development and income levels, as well as different geographical extensions, among which several Small Island Developing States (SIDS), are included within this application with the idea of exploring how those different aspects influence on the absolute and relative results.

Table 5-1 summarizes the projected populations to year 2015 as well as the life expectancies at birth for the analysed countries in the LAC region. Table 5-2 shows the age range distribution for the analysed countries in 5-years spans.

Table 5-1 Population and life expectancy at birth for selected countries in LAC region

Country	Population (2015)	Life expectancy at birth
Aruba	104,000	76.0
Argentina	42,174,000	77.1
Antigua and Barbuda	91,000	76.7
Belize	348,000	74.8
Bolivia	11,025,000	68.4
Barbados	289,000	76.1
Chile	17,923,000	81.0
Colombia	49,529,000	74.9
Costa Rica	5,001,000	80.9
Cuba	11,251,000	80.1
Dominican Republic	10,651,000	74.4
Ecuador	16,224,000	77.6
Grenada	106,000	73.8
Guatemala	16,255,000	73.4
Honduras	8,424,000	75.1
Haiti	10,603,000	64.3
Jamaica	2,815,000	74.1
Saint Lucia	185,000	75.4
Mexico	125,236,000	78.5
Nicaragua	6,258,000	76.2
Panama	3,988,000	78.5
Peru	31,161,000	76.1
Puerto Rico	3,681,000	74.9
Paraguay	7,033,000	79.6
El Salvador	6,427,000	73.6
Trinidad and Tobago	1,345,000	70.3
St. Vincent and the Grenadines	111,000	73.0
Venezuela	31,292,000	75.3
Virgin Islands	106,000	81.1

Table 5-2 Age range distribution for selected countries in LAC region

Country	Age range (%)																				
	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75-79	80-84	85-89	90-94	95-99	100+
Aruba	4.81	6.73	6.73	7.69	6.73	4.81	5.77	6.73	7.69	7.69	8.65	7.69	6.73	4.81	2.88	1.92	0.96	0.96	0.00	0.00	0.00
Argentina	8.16	7.98	7.75	7.97	8.04	7.80	7.49	7.60	6.34	5.52	5.15	4.73	4.28	3.56	2.79	2.10	1.46	0.84	0.34	0.10	0.02
Antigua and Barbuda	7.69	7.69	8.79	8.79	8.79	7.69	6.59	5.49	7.69	8.79	6.59	5.49	3.30	2.20	2.20	1.10	1.10	0.00	0.00	0.00	0.00
Belize	11.21	10.92	10.63	10.34	9.48	8.62	8.33	7.18	6.03	4.89	3.74	2.59	2.01	1.44	0.86	0.86	0.57	0.29	0.00	0.00	0.00
Bolivia	11.85	11.23	11.04	10.36	9.72	8.27	6.99	6.05	5.45	4.51	3.76	3.15	2.54	1.99	1.39	0.93	0.50	0.21	0.05	0.01	0.00
Barbados	6.23	6.23	6.23	6.57	7.27	7.27	7.27	6.92	7.27	7.27	7.61	6.92	5.54	4.15	2.77	2.08	1.38	0.69	0.35	0.00	0.00
Chile	6.81	6.83	6.93	7.44	8.32	8.17	7.38	6.53	6.89	6.85	6.91	5.88	4.50	3.53	2.73	1.86	1.28	0.73	0.31	0.10	0.02
Colombia	9.00	9.07	8.92	8.85	8.70	8.17	7.65	7.08	6.26	6.19	5.45	4.45	3.57	2.58	1.69	1.13	0.70	0.35	0.14	0.03	0.01
Costa Rica	7.34	7.36	7.96	8.36	8.80	9.24	8.44	7.38	6.38	6.32	6.14	4.94	3.86	2.64	1.86	1.34	0.86	0.50	0.20	0.08	0.02
Cuba	4.67	5.00	5.90	6.20	6.67	7.21	6.07	6.01	8.74	9.23	8.95	5.82	5.50	4.27	3.60	2.81	1.78	0.98	0.42	0.13	0.04
Dominican Republic	9.91	9.97	9.72	9.18	8.93	8.19	7.45	6.57	6.02	5.47	4.85	4.04	3.12	2.21	1.57	1.23	0.82	0.45	0.21	0.08	0.03
Ecuador	9.91	9.77	9.60	9.15	8.74	8.35	7.50	6.86	6.19	5.44	4.61	3.87	3.19	2.25	1.73	1.31	0.86	0.45	0.17	0.04	0.01
Grenada	9.43	8.49	8.49	9.43	9.43	10.38	8.49	6.60	4.72	4.72	5.66	3.77	2.83	1.89	1.89	1.89	0.94	0.94	0.00	0.00	0.00
Guatemala	14.27	13.18	12.22	10.93	9.57	7.93	6.76	5.47	4.35	3.47	2.83	2.32	2.03	1.66	1.17	0.87	0.58	0.28	0.09	0.02	0.00
Honduras	12.03	11.37	10.91	10.65	10.10	8.87	7.61	6.24	4.97	4.20	3.43	2.79	2.22	1.58	1.15	0.85	0.58	0.30	0.12	0.02	0.00
Haiti	11.80	11.40	10.98	10.53	9.70	8.89	7.99	6.05	4.73	4.25	3.71	2.98	2.42	1.69	1.35	0.89	0.45	0.15	0.04	0.01	0.00
Jamaica	8.53	8.63	8.85	10.27	8.88	7.53	6.47	6.00	6.32	6.61	5.75	4.33	3.69	2.45	2.02	1.56	1.10	0.64	0.28	0.07	0.00
Saint Lucia	7.57	7.57	8.11	8.65	8.65	7.57	7.57	7.03	7.03	7.03	5.95	4.86	3.78	2.70	2.16	1.62	1.08	0.54	0.54	0.00	0.00
Mexico	8.85	9.19	9.40	9.45	8.84	8.00	7.34	7.16	7.08	5.86	4.76	3.94	3.34	2.33	1.83	1.20	0.79	0.42	0.17	0.04	0.01
Nicaragua	10.83	10.77	10.29	10.37	10.19	8.88	7.99	6.57	5.39	4.41	3.74	3.24	2.52	1.44	1.29	0.94	0.61	0.34	0.14	0.03	0.00
Panama	9.28	9.20	9.10	8.78	8.20	7.85	7.47	7.17	6.75	5.99	5.14	4.19	3.28	2.53	1.93	1.38	0.90	0.50	0.25	0.08	0.03
Peru	9.39	9.30	9.31	9.30	9.11	8.49	7.67	7.19	6.32	5.52	4.76	3.85	3.08	2.36	1.75	1.27	0.78	0.37	0.13	0.04	0.01
Puerto Rico	6.00	6.19	6.71	7.47	7.61	7.17	7.06	7.04	6.68	6.49	6.30	5.62	5.16	4.67	3.48	2.61	1.79	1.11	0.57	0.19	0.05
Paraguay	11.08	10.46	10.24	9.91	9.47	8.86	7.95	6.30	5.06	4.59	4.04	3.47	2.87	2.09	1.49	1.05	0.60	0.33	0.11	0.03	0.00
El Salvador	9.74	9.51	9.60	11.14	10.56	8.82	7.11	6.11	5.31	4.73	4.08	3.25	2.72	2.19	1.88	1.42	0.93	0.51	0.25	0.09	0.03
Trinidad and Tobago	6.99	7.14	6.69	6.25	6.77	8.33	9.44	7.58	6.84	6.32	7.21	6.02	4.91	3.64	2.60	1.64	0.97	0.45	0.15	0.07	0.00
St. Vincent and the Grenadines	8.11	8.11	8.11	9.01	9.01	8.11	7.21	7.21	6.31	6.31	6.31	5.41	3.60	2.70	1.80	1.80	0.90	0.00	0.00	0.00	0.00
Venezuela	9.45	9.35	9.12	8.84	8.67	8.55	7.80	7.08	6.08	5.72	5.18	4.14	3.41	2.57	1.74	1.12	0.69	0.34	0.11	0.03	0.00
Virgin Islands	7.55	6.60	6.60	6.60	6.60	4.72	4.72	5.66	5.66	6.60	7.55	7.55	6.60	6.60	4.72	2.83	1.89	0.94	0.00	0.00	0.00

Using the probabilistic risk framework explained in Chapter 2, together with the human vulnerability functions developed using the proposed procedure the *AAD* at country level is obtained and is shown in Figure 5-4 and Table 5-3. These results, combined with the data of Table 5-2, allow estimating the AAD_r.

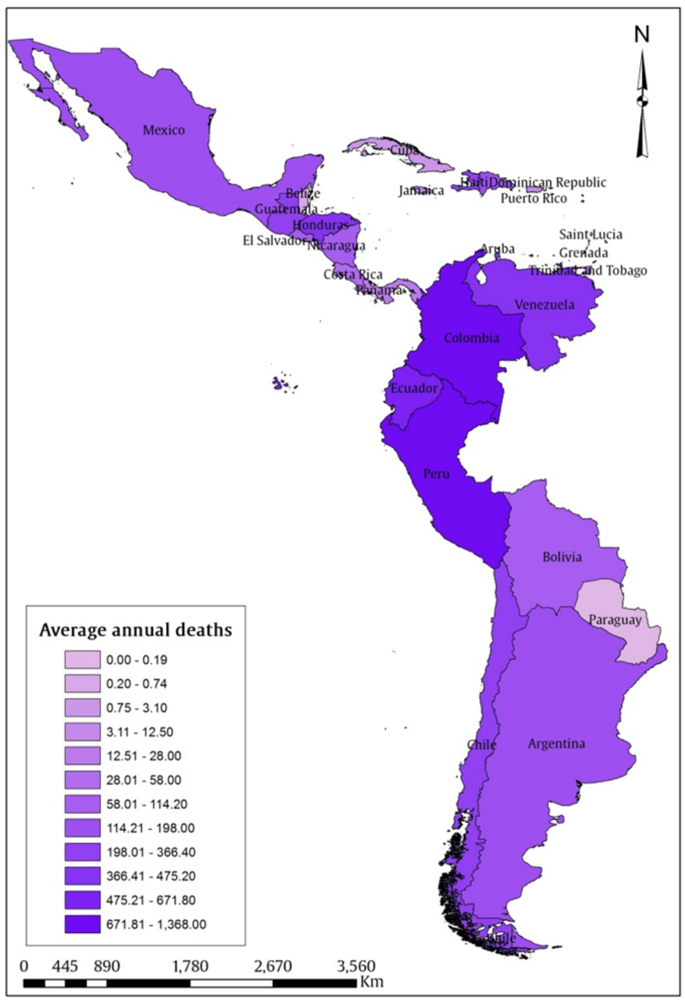


Figure 5-4 *AAD* at country level with 60% occupation level

Table 5-3 *AAD* for selected countries in LAC region with 60% occupation level

Country	*AAD*
Aruba	0.011
Argentina	198
Antigua and Barbuda	0.035
Belize	0.738
Bolivia	98
Barbados	3
Chile	120
Colombia	1,357
Costa Rica	58
Cuba	3.096
Dominican Republic	146
Ecuador	672
Grenada	0.090
Guatemala	366
Honduras	475
Haiti	277
Jamaica	12
Saint Lucia	0.047
Mexico	144
Nicaragua	114
Panama	28
Peru	1,369
Puerto Rico	9.210
Paraguay	0.071
El Salvador	106
Trinidad and Tobago	51
St. Vincent and the Grenadines	0.030
Venezuela	396
Virgin Islands	0.192

By combining the data from the life expectancies at birth with the AAD_i, results, YLL_i is obtained using the proposed methodology and the results are presented in Table 5-4 and Figure 5-5.

Table 5-4 YLL_i and YLL for selected countries in LAC region

Country	YLLi by age range																					Total
	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75-79	80-84	85-89	90-94	95-99	100+	
Aruba	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-	0.5
Argentina	1,205.5	1,099.5	991.4	940.4	869.2	765.7	661.7	595.9	434.0	323.8	250.6	183.6	123.6	67.6	25.4	-	-	-	-	-	-	8,538.0
Antigua and Barbuda	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	-	-	-	-	-	-	1.6
Belize	6.0	5.4	4.9	4.4	3.7	3.0	2.6	2.0	1.4	1.0	0.6	0.3	0.2	0.1	0.0	-	-	-	-	-	-	35.6
Bolivia	766.9	671.3	605.7	517.5	438.1	332.1	246.4	183.5	138.6	92.5	58.7	33.7	14.7	1.8	-	-	-	-	-	-	-	4,101.5
Barbados	13.2	12.3	11.4	11.1	11.2	10.2	9.1	7.7	7.0	6.0	5.2	3.7	2.2	1.0	0.3	-	-	-	-	-	-	111.8
Chile	1,862.3	1,749.4	1,654.3	1,645.9	1,696.1	1,524.1	1,247.7	989.7	924.6	799.9	686.6	481.6	289.9	165.9	81.0	22.7	-	-	-	-	-	15,821.7
Colombia	8,838.4	8,296.3	7,551.0	6,892.5	6,185.9	5,251.6	4,402.6	3,594.6	2,751.9	2,301.7	1,655.9	1,049.9	601.2	259.0	54.9	-	-	-	-	-	-	59,687.4
Costa Rica	334.8	314.3	316.8	308.4	299.0	287.1	237.7	186.4	142.5	122.8	101.5	67.3	41.3	20.6	9.1	2.7	-	-	-	-	-	2,792.1
Cuba	11.2	11.2	12.4	12.0	11.9	11.7	8.9	7.9	10.2	9.3	7.6	4.1	3.0	1.7	0.8	0.2	-	-	-	-	-	124.3
Dominican Republic	1,044.3	977.2	881.2	765.4	678.9	562.5	457.0	355.3	281.2	215.7	155.7	100.0	54.3	22.3	4.4	-	-	-	-	-	-	6,555.4
Ecuador	4,997.0	4,600.5	4,196.9	3,692.9	3,235.1	2,808.7	2,272.6	1,848.0	1,460.6	1,100.5	777.4	522.7	323.2	152.6	59.3	0.9	-	-	-	-	-	32,048.9
Grenada	0.6	0.5	0.5	0.5	0.4	0.4	0.3	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	-	-	-	-	-	-	3.9
Guatemala	3,707.5	3,181.6	2,727.5	2,238.9	1,785.1	1,333.5	1,013.1	719.3	492.4	329.2	216.7	135.1	81.1	35.9	3.9	-	-	-	-	-	-	18,000.9
Honduras	4,148.6	3,653.2	3,245.2	2,914.6	2,525.1	2,005.8	1,540.4	1,115.7	770.5	551.2	368.4	233.3	132.9	57.0	14.2	-	-	-	-	-	-	23,276.1
Haiti	2,020.3	1,794.5	1,575.6	1,364.9	1,122.9	906.9	703.9	449.6	285.4	198.0	121.2	56.2	12.1	-	-	-	-	-	-	-	-	10,611.4
Jamaica	76.3	71.8	68.1	72.6	57.2	43.8	33.6	27.4	25.0	22.0	15.5	9.0	5.4	2.0	0.4	-	-	-	-	-	-	530.1
Saint Lucia	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	-	-	-	-	-	-	2.0
Mexico	968.3	939.2	893.5	829.8	712.7	587.6	486.2	422.8	367.1	261.6	178.2	119.2	77.0	37.0	15.8	1.7	-	-	-	-	-	6,897.7
Nicaragua	912.4	845.5	749.0	695.6	625.6	494.4	399.0	290.4	207.4	144.6	101.3	69.3	39.5	14.3	5.5	-	-	-	-	-	-	5,593.6
Panama	197.3	182.8	168.1	149.8	128.5	112.0	96.2	82.3	68.0	52.0	37.4	24.6	14.7	7.8	3.2	0.4	-	-	-	-	-	1,325.2
Peru	9,455.6	8,734.9	8,103.8	7,459.0	6,686.0	5,648.2	4,575.0	3,801.1	2,907.3	2,160.6	1,538.3	981.2	572.9	277.3	86.2	-	-	-	-	-	-	62,987.1
Puerto Rico	40.0	38.4	38.6	39.5	36.7	31.3	27.6	24.2	19.9	16.4	13.0	9.0	5.9	3.2	0.8	-	-	-	-	-	-	344.6
Paraguay	0.6	0.5	0.5	0.4	0.4	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	-	-	-	-	-	3.7
El Salvador	733.6	665.6	621.3	662.0	571.8	430.8	309.6	233.8	174.8	130.8	91.1	55.5	32.0	14.2	2.2	-	-	-	-	-	-	4,729.0
Trinidad and Tobago	242.5	229.4	197.9	168.7	165.5	182.4	182.6	127.3	97.3	73.7	65.7	39.4	19.6	5.2	-	-	-	-	-	-	-	1,797.1
St. Vincent and the Grenadines	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-	-	1.2
Venezuela	2,722.8	2,510.1	2,266.2	2,022.1	1,812.5	1,616.7	1,322.0	1,060.0	789.9	629.8	467.2	292.0	172.6	79.3	19.2	-	-	-	-	-	-	17,782.2
Virgin Islands	1.1	0.9	0.9	0.8	0.7	0.5	0.4	0.5	0.4	0.4	0.4	0.3	0.2	0.2	0.1	0.0	-	-	-	-	-	8.0

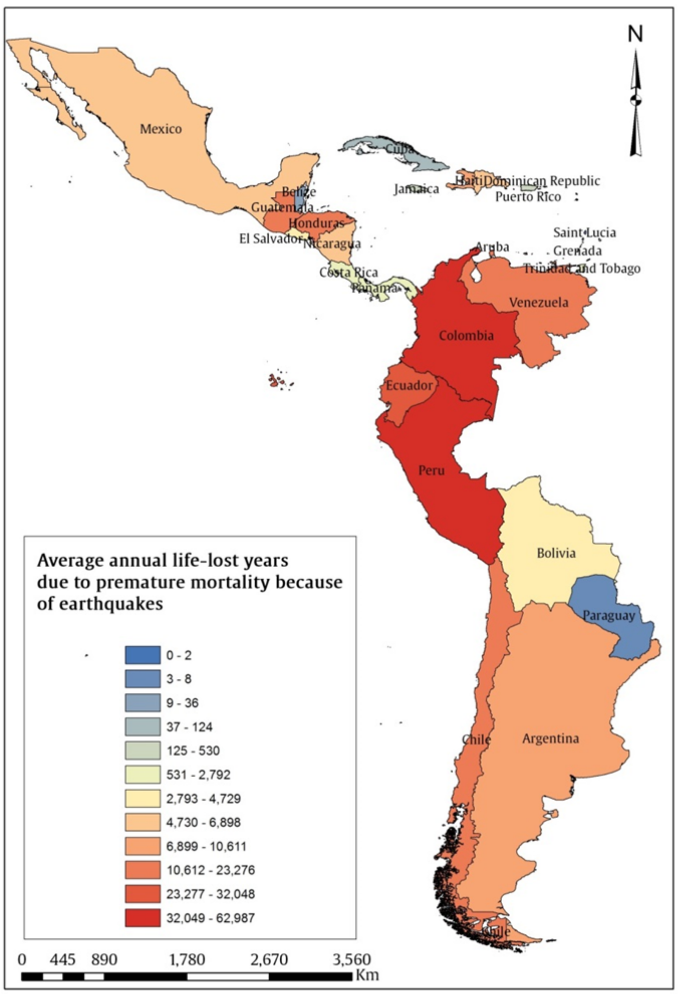


Figure 5-5 Average annual life-lost years due to premature mortality because of earthquakes in Latin America and the Caribbean

Table 5-5 presents the GDP per capita (World Bank, 2011) and the sum of the working age, *YLL*, which are the data required for the estimation of the average annual lost economic production due to premature mortality because of earthquakes obtained by applying equation 5.8.

Table 5-5 GDP per capita and working age *YLL* for selected countries in LAC region

Country	GDP per capita (USD)		Working age *YLL*
Aruba	$	25,355	0.3
Argentina	$	14,715	5,149
Antigua and Barbuda	$	13,342	1.0
Belize	$	4,894	19
Bolivia	$	2,868	2,056
Barbados	$	14,917	74
Chile	$	15,732	3,542
Colombia	$	7,831	34,688
Costa Rica	$	10,185	1,794
Cuba	$	6,051	87
Dominican Republic	$	5,879	3,626
Ecuador	$	6,003	18,042
Grenada	$	7,891	2.3
Guatemala	$	3,478	8,345
Honduras	$	2,291	12,158
Haiti	$	820	5,221
Jamaica	$	5,290	312
Saint Lucia	$	7,328	1.3
Mexico	$	10,307	4,042
Nicaragua	$	1,851	3,067
Panama	$	11,037	765
Peru	$	6,662	36,329
Puerto Rico	$	28,529	224
Paraguay	$	4,265	2.0
El Salvador	$	3,826	2,692
Trinidad and Tobago	$	18,373	1,122
St. Vincent and the Grenadines	$	6,486	0.7
Venezuela	$	14,415	10,185
Virgin Islands	$	18,728	4.8

Figure 5-6 shows the average annual lost production due to premature mortality due to earthquakes whereas Table 5-6 shows the obtained value as well as that obtained for the physical risk assessment and the ratio between these two figures. This last value is also shown in a graphical way in Figure 5-7.

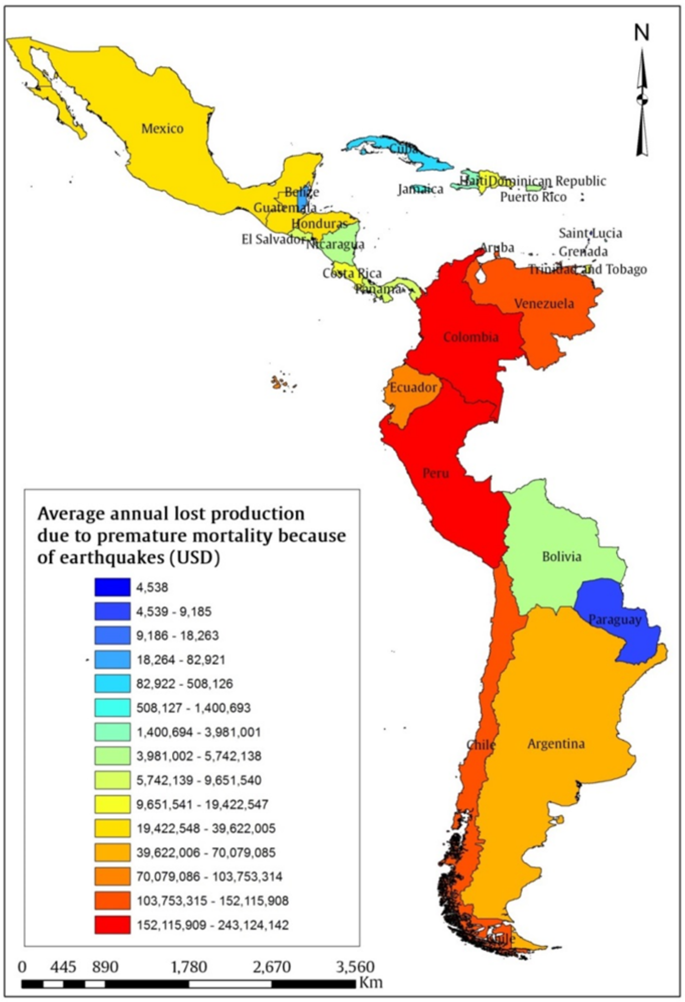


Figure 5-6 Average annual lost production due to premature mortality because of earthquakes in Latin America and the Caribbean

Table 5-6 Summary of physical and human losses for selected countries in LAC region

Country	AAL (USD)	Average annual lost production (USD)	AAL/AALP Ratio (%)
Aruba	$ 310,000	$ 7,506	2.4
Argentina	$ 383,210,000	$ 75,761,173	19.8
Antigua and Barbuda	$ 2,090,000	$ 13,035	0.6
Belize	$ 600,000	$ 93,832	15.6
Bolivia	$ 22,850,000	$ 5,895,418	25.8
Barbados	$ 8,470,000	$ 1,096,707	12.9
Chile	$ 1,236,900,000	$ 55,719,254	4.5
Colombia	$ 915,750,000	$ 271,647,086	29.7
Costa Rica	$ 134,920,000	$ 18,270,079	13.5
Cuba	$ 8,580,000	$ 524,923	6.1
Dominican Republic	$ 139,350,000	$ 21,317,316	15.3
Ecuador	$ 551,090,000	$ 108,301,998	19.7
Grenada	$ 120,000	$ 18,263	15.2
Guatemala	$ 248,830,000	$ 29,021,719	11.7
Honduras	$ 178,590,000	$ 27,851,084	15.6
Haiti	$ 48,120,000	$ 4,280,646	8.9
Jamaica	$ 13,910,000	$ 1,647,874	11.8
Saint Lucia	$ 130,000	$ 9,185	7.1
Mexico	$ 955,500,000	$ 41,663,518	4.4
Nicaragua	$ 53,260,000	$ 5,677,365	10.7
Panama	$ 62,680,000	$ 8,448,174	13.5
Peru	$ 1,644,020,000	$ 242,012,194	14.7
Puerto Rico	$ 113,010,000	$ 6,378,202	5.6
Paraguay	$ 1,070,000	$ 8,683	0.8
El Salvador	$ 85,360,000	$ 10,300,469	12.1
Trinidad and Tobago	$ 282,830,000	$ 20,618,415	7.3
St. Vincent and the Grenadines	$ 20,000	$ 4,817	24.1
Venezuela	$ 779,850,000	$ 146,809,636	18.8
Virgin Islands	$ 1,460,000	$ 89,644	6.1

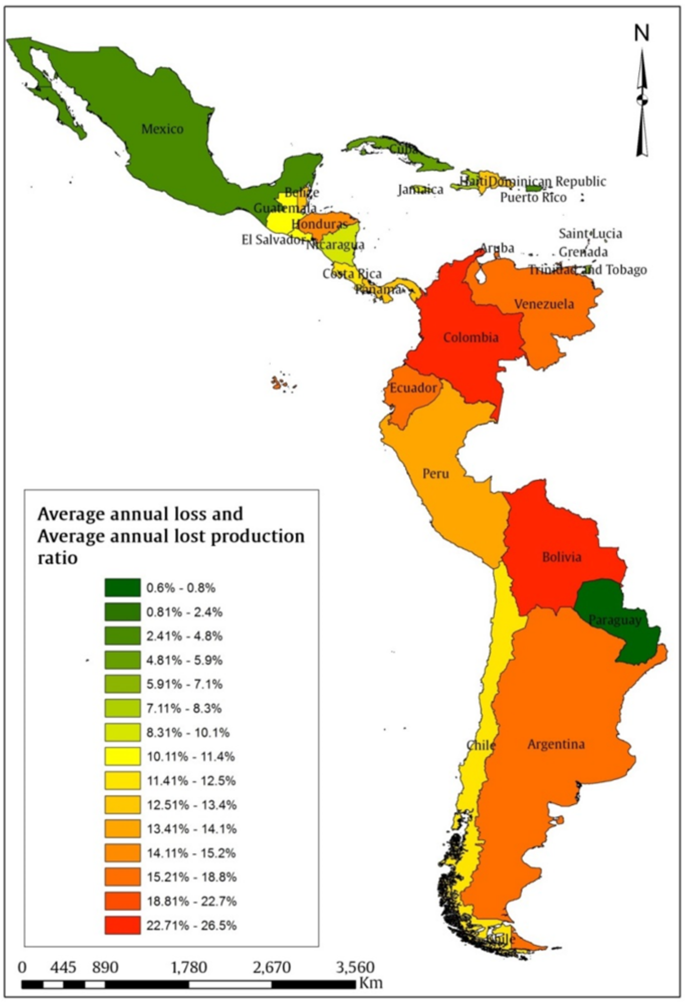


Figure 5-7 Average annual human and physical loss stock ratio for Latin America and the Caribbean

With these results, a ranking of the considered countries is shown in Figure 5-8 from where it can be seen cases like Colombia where, relatively speaking, a large *AAD* is expected due to the existence of several large urban settlements located in medium and high seismic hazard areas. This ranking provides information showing in which countries, in relative terms, should be more investment in corrective measures regarding seismic safety with the objective of reducing mortality. It is also interesting the cases of Chile and Mexico, two countries with significant seismic hazard but, at the same time, where state-of-the-art building code requirements and high enforcement levels exist, where, important corrective measures regarding seismic safety have been undertaken.

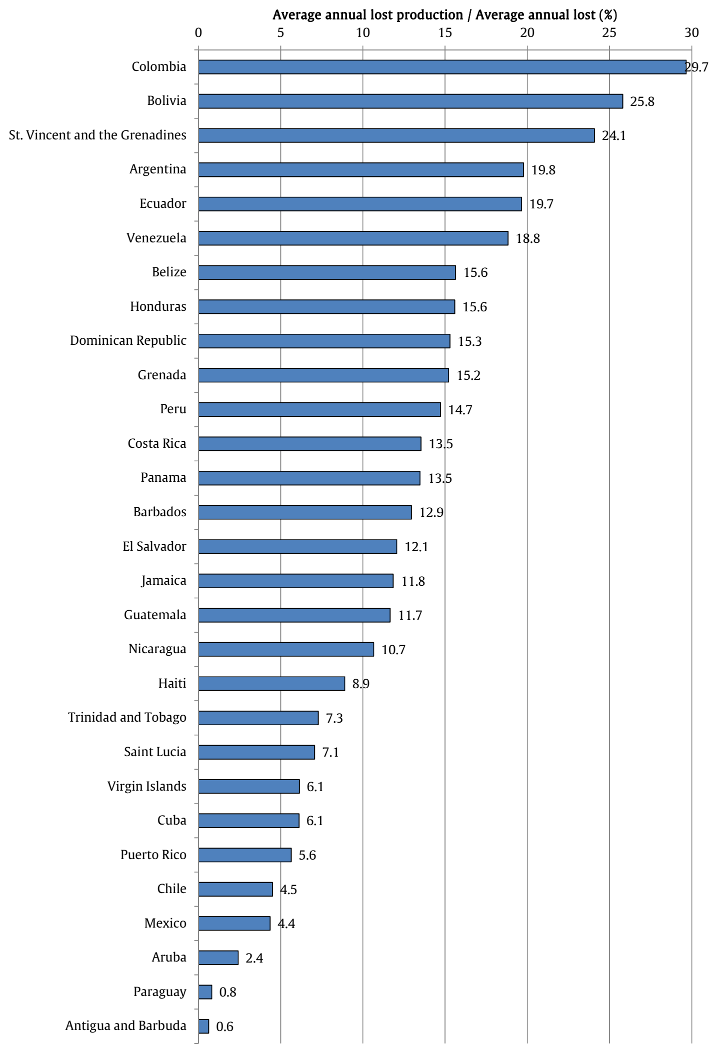


Figure 5-8 Average annual human and physical loss stock ratio ranking for Latin America and the Caribbean

Since the obtained average annual lost production is proposed as the minimum public investment on seismic safety, the obtained results are compared against the GFCF, an important macroeconomic indicator regarding investment, and a ranking for the region shown in Figure 5-9 has been obtained. From this ranking, it can be seen which are the countries expected to spend more on seismic safety as a share of the overall investment. This result also combines seismic risk levels, considering the human stock dimension and the macroeconomic conditions. Countries with the largest relative exposure to important seismic hazard levels and also those where the geographical diversification is not possible due to their extent, are found in the top positions of the ranking together with those where no significant investment on seismic safety have occurred. Again, the presence of Chile and Mexico in middle and bottom positions, despite their important seismic hazard levels, show how the already made investments on this topic are reflected in the final results.

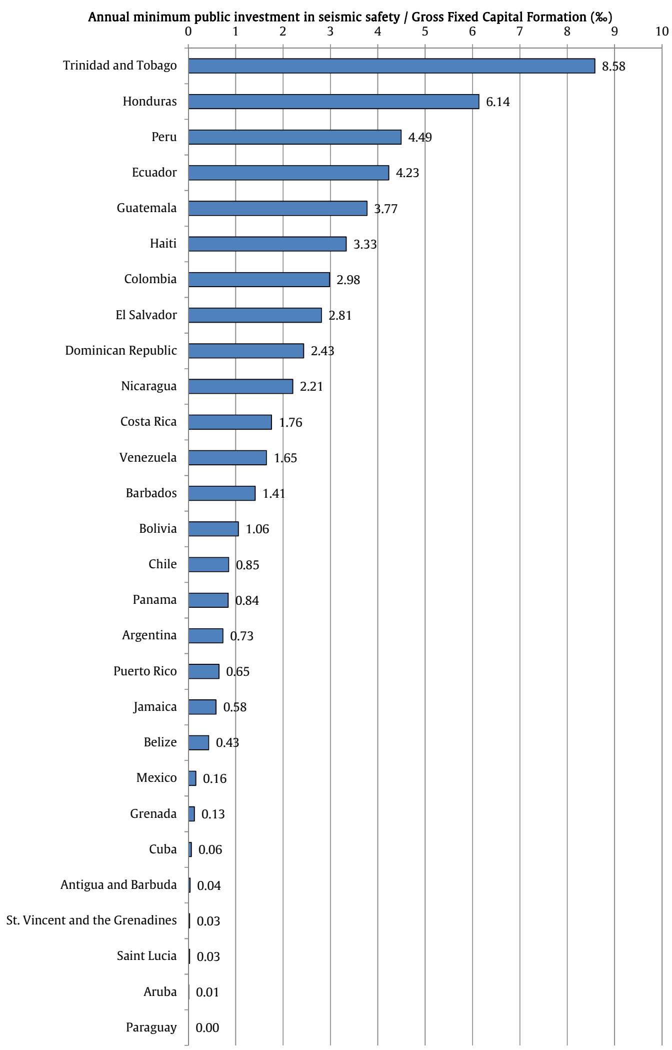


Figure 5-9 Average annual lost production due to premature mortality because of earthquakes and GFCF ratio ranking for Latin America and the Caribbean

With the data of the last ranking, a new one which only considers Small Islands Developing States (SIDS) is shown in Figure 5-10 from where it can be seen that, due to the lack of possibilities to geographically diversify exposed assets, population and industries, important shares of the investment would be required for seismic safety in those countries where there is significant seismic hazard such as Trinidad and Tobago, Haiti, Dominican Republic, Barbados and Jamaica.

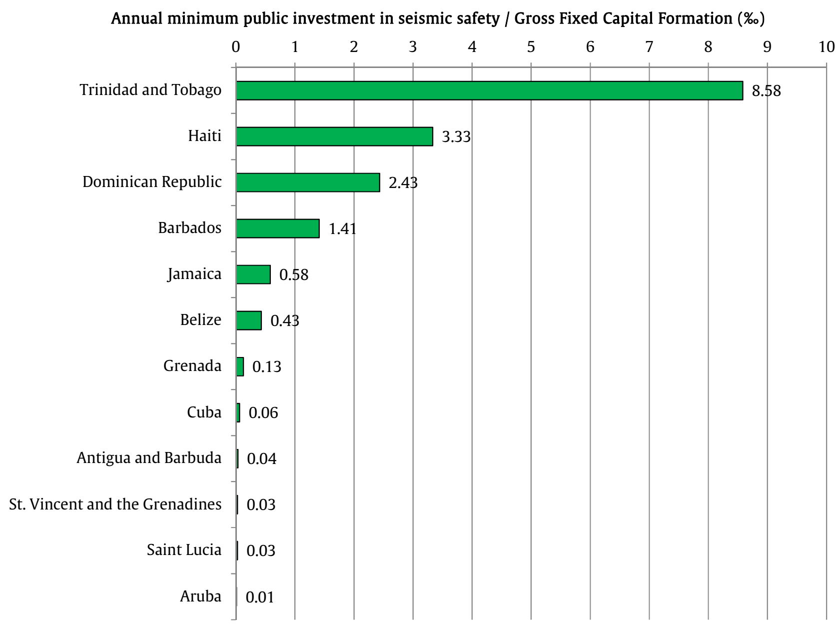


Figure 5-10 Average annual lost production due to premature mortality because of earthquakes and GFCF ratio ranking for SIDS in LAC

The methodology was also applied at national level in Spain using the same input data and information sources. A total projected population of 46,122,000 inhabitants for year 2015 and a life expectancy at birth of 82.3 years are used. Table 5-7 shows the age distribution, for 5 years spans, in Spain.

Table 5-7 Age distribution in Spain

Age range	Relative number of inhabitants
0 to 4	4.65%
5 to 9	5.28%
10 to 14	4.95%
15 to 19	4.53%
20 to 24	4.84%
25 to 29	5.34%
30 to 34	6.61%
35 to 39	8.39%
40 to 44	8.57%
45 to 49	8.04%
50 to 54	7.65%
55 to 59	6.76%
60 to 64	5.59%
65 to 69	5.10%
70 to 74	4.29%
75 to 79	3.47%
80 to 84	3.11%
85 to 89	1.86%
90 to 94	0.75%
95 to 99	0.17%
100+	0.02%
TOTAL	100%

In this case *AAD* is estimated in 1.44, a considerable lower value if compared to other countries with similar geographical extent in the LAC region but well explained for the low seismicity in Spain. Table 5-8 shows the AAD_i whereas Table 5-8 shows the YLL_i obtained after applying the proposed methodology.

Table 5-8 *AADi* for Spain

Age range	*AADi*
0 to 4	0.067
5 to 9	0.076
10 to 14	0.071
15 to 19	0.065
20 to 24	0.070
25 to 29	0.077
30 to 34	0.095
35 to 39	0.121
40 to 44	0.123
45 to 49	0.116
50 to 54	0.110
55 to 59	0.097
60 to 64	0.081
65 to 69	0.073
70 to 74	0.062
75 to 79	0.050
80 to 84	0.045
85 to 89	0.027
90 to 94	0.011
95 to 99	0.002
100+	0.000
TOTAL	1.44

Table 5-9 *YLLi* for Spain

Age range	*YLLi*
0 to 4	5.3
5 to 9	5.7
10 to 14	5.0
15 to 19	4.2
20 to 24	4.2
25 to 29	4.2
30 to 34	4.7
35 to 39	5.4
40 to 44	4.9
45 to 49	4.0
50 to 54	3.3
55 to 59	2.4
60 to 64	1.6
65 to 69	1.1
70 to 74	0.6
75 to 79	0.3
80 to 84	0.1
85 to 89	-
90 to 94	-
95 to 99	-
100+	-
TOTAL	57

By considering the number of lost-life years of the working age range and a GDP per capita of USD 29,863 (World Bank, 2011), the average annual economic lost production due to premature mortality because of earthquake is equal to USD 1,164,656 or, what is the same, 1.0% of the physical *AAL*. In terms of the GFCF, the obtained result corresponds to 0.005‰.

5.6 Application of the methodology at subnational level

In this section the results of the proposed methodology are applied at a subnational level in Colombia. For this subnational assessment, the seismic hazard model corresponds to the latest study available for the country (Salgado-Gálvez et al., 2015c) whose details can also be found in Annex 1. The exposure database is again that one developed for the GAR15 but data for life expectancy at birth, projected population to 2015, GDP per capita[8] and distribution of it in 5-years age ranges was obtained from the Colombian statistics department – DANE at subnational level (DANE, 2015) and several entries were updated. This case

[8] An exchange rate of 1USD=3,000 COP has been used in this thesis

study shows how, when the required data are disaggregated at subnational level and important differences exist among them, it is possible to identify where the largest resources have to be placed in terms of public investment on seismic safety.

Table 5-10 shows the projected population to year 2015 as well as the life expectancy at birth of the 27 analysed departments which correspond to those with seismic hazard and risk levels. Table 5-11 shows the age distribution in 5-years span. Important differences in the life expectancies at birth can be seen for less developed departments such as Chocó, Arauca and Caquetá. This occurs despite the important contributions they have in terms of revenues given their mining and oil industries which clearly has not been reflected in common wealth. Among those three mentioned departments, Chocó and Arauca have important seismic hazard levels.

Table 5-10 Population and life expectancy at birth for selected departments in Colombia

Department	Population (2015)	Life expectancy at birth
Antioquia	6,456,207	75.1
Arauca	262,315	69.9
Atlántico	2,461,001	75.5
Bogotá D. C.	7,878,783	78.0
Bolívar	2,097,086	74.2
Boyacá	1,276,367	75.3
Caldas	988,003	74.5
Caquetá	477,619	69.5
Casanare	350,438	70.0
Cauca	1,379,070	71.9
Cesar	1,028,880	73.8
Chocó	500,076	69.3
Córdoba	1,709,603	73.5
Cundinamarca	2,680,041	74.4
La Guajira	957,814	74.4
Huila	1,154,804	73.2
Magdalena	1,259,667	74.0
Meta	961,292	71.6
Nariño	1,744,275	73.2
Norte Santander	1,355,723	72.6
Putumayo	345,204	72.0
Quindío	565,266	74.5
Risaralda	463,438	74.7
Santander	2,061,095	75.3
Sucre	851,526	74.4
Tolima	1,408,274	73.3
Valle del Cauca	4,613,377	75.3

Table 5-11 Age distribution for selected departments in Colombia

Department	Age range (%)																
	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75-79	80+
Antioquia	8.23	8.07	8.13	8.53	8.96	8.53	7.55	6.79	6.03	6.34	6.09	5.05	3.91	2.89	2.00	1.43	1.46
Arauca	12.68	12.28	11.98	10.45	9.01	7.14	6.22	5.21	5.11	4.73	4.26	3.48	2.40	1.81	1.35	1.04	0.84
Atlántico	8.73	8.75	8.89	8.79	8.65	8.43	8.00	6.96	5.98	6.06	5.77	4.57	3.49	2.55	1.71	1.31	1.36
Bogotá D. C.	7.66	7.59	7.68	8.15	8.50	8.07	8.35	7.80	6.81	6.56	6.22	5.15	3.93	2.92	2.01	1.31	1.27
Bolívar	9.84	9.69	9.70	9.75	9.11	8.02	7.06	6.16	5.60	5.59	5.12	4.20	3.22	2.48	1.71	1.33	1.41
Boyacá	8.51	9.02	9.54	9.09	7.86	6.87	6.36	6.18	6.27	6.23	5.56	4.80	3.94	3.19	2.42	2.01	2.16
Caldas	8.03	8.16	8.23	8.19	8.48	8.75	6.43	5.91	5.60	6.30	6.12	5.55	4.59	3.37	2.44	1.83	2.01
Caquetá	11.35	10.94	10.88	10.33	9.45	8.39	6.68	5.83	5.14	5.08	4.30	3.41	2.70	2.02	1.43	1.06	1.01
Casanare	10.38	10.40	10.43	10.21	9.99	8.86	7.04	6.83	6.17	3.95	4.64	3.56	2.66	1.95	1.35	0.86	0.71
Cauca	9.66	9.23	9.50	9.84	9.31	8.05	7.39	6.59	5.50	5.22	4.77	4.05	3.29	2.63	1.97	1.51	1.46
Cesar	10.73	10.59	10.61	10.22	9.44	8.24	6.56	6.05	5.53	5.32	4.58	3.66	2.83	2.17	1.44	1.05	0.98
Chocó	13.15	12.68	11.95	11.00	10.40	9.41	5.91	4.68	3.81	3.67	3.30	3.12	2.20	1.63	1.04	1.12	0.92
Córdoba	10.63	10.22	9.89	9.64	9.59	8.22	6.82	6.02	5.42	5.41	4.75	3.87	2.99	2.29	1.63	1.26	1.34
Cundinamarca	9.03	8.94	8.99	8.97	9.06	8.70	7.03	6.26	5.87	5.99	5.54	4.52	3.50	2.65	1.96	1.49	1.51
La Guajira	13.31	12.08	10.85	9.79	8.80	8.80	7.06	6.06	4.93	4.39	3.68	3.04	2.16	1.76	1.26	1.05	0.98
Huila	9.88	9.70	9.71	9.73	9.61	8.15	7.00	6.16	5.54	5.42	5.01	4.12	3.20	2.43	1.72	1.28	1.33
Magdalena	11.00	11.00	10.95	10.45	8.73	7.35	6.23	5.68	5.26	5.26	4.74	3.89	3.07	2.34	1.58	1.22	1.25
Meta	9.77	9.58	9.39	9.05	9.07	8.66	7.49	6.81	6.02	5.82	5.13	4.06	3.04	2.27	1.58	1.17	1.08
Nariño	9.43	9.33	9.54	9.46	8.70	8.12	7.77	6.97	5.84	5.68	4.70	3.86	3.12	2.56	1.92	1.46	1.54
Norte Santander	9.33	9.25	9.62	10.06	9.06	8.09	7.17	6.18	5.62	5.66	5.23	4.33	3.38	2.54	1.80	1.34	1.34
Putumayo	11.45	11.06	11.12	10.92	9.94	8.03	6.97	6.28	5.22	4.76	3.79	3.07	2.31	1.82	1.30	1.00	0.95
Quindío	8.13	8.00	8.05	8.36	8.83	7.64	6.67	6.21	5.83	6.49	6.37	5.52	4.55	3.41	2.43	1.77	1.75
Risaralda	8.39	8.34	8.42	8.82	9.24	7.95	6.99	6.49	5.73	6.17	5.96	5.19	4.23	3.08	2.14	1.46	1.39
Santander	8.05	8.09	8.23	8.80	8.81	8.08	7.45	6.82	6.27	6.43	5.98	4.81	3.76	2.95	2.16	1.61	1.69
Sucre	9.90	9.72	9.83	9.86	9.64	8.18	6.58	5.83	5.33	5.59	4.90	4.10	3.22	2.64	1.79	1.43	1.46
Tolima	9.03	9.07	9.27	9.19	8.87	7.84	5.71	5.52	5.45	5.88	5.92	4.97	4.10	3.18	2.38	1.77	1.85
Valle del Cauca	7.88	7.76	7.85	8.46	8.81	8.32	7.69	7.02	6.38	6.45	6.12	5.01	3.95	2.95	2.11	1.62	1.63

Figure 5-11 shows the *AAD* results by department from where it can be seen that the largest values correspond to locations where, besides intermediate and high seismic hazard levels, there are large urban settlements and/or population density.

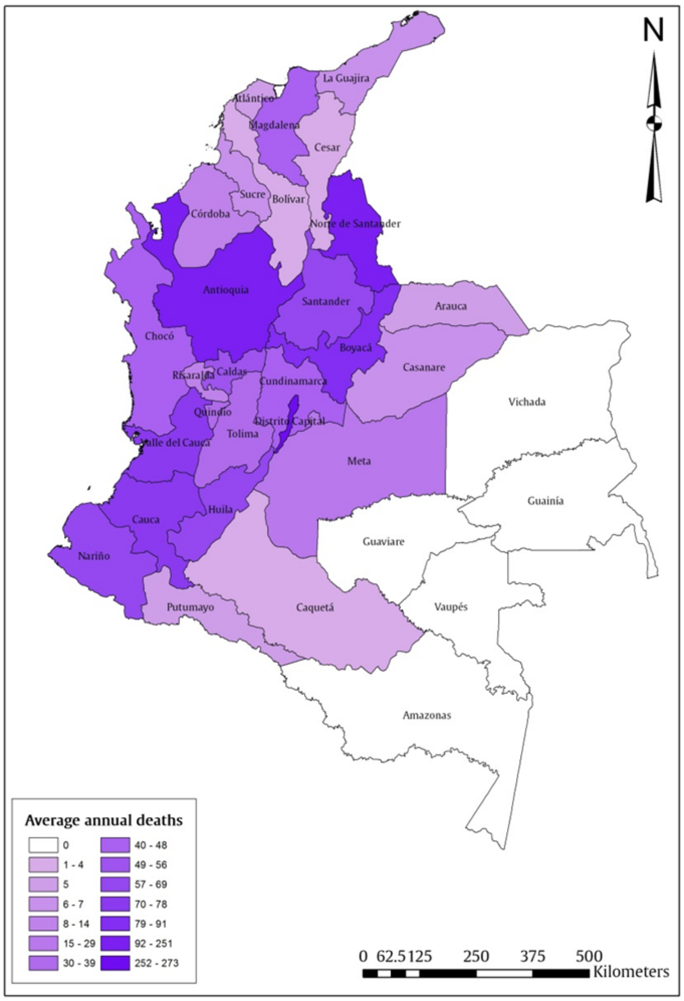


Figure 5-11 ***AAD*** **at department level for Colombia**

These results combined with the age distribution shown in Table 5-11 allow obtaining the AAD_i for each department as shown in Table 5-12.

Table 5-12 *AAD* for selected departments in Colombia

Department	*AAD*
Antioquia	251
Arauca	5
Atlántico	5
Bogotá D. C.	273
Bolívar	4
Boyacá	91
Caldas	56
Caquetá	3
Casanare	7
Cauca	78
Cesar	4
Chocó	48
Córdoba	14
Cundinamarca	47
La Guajira	6
Huila	69
Magdalena	47
Meta	29
Nariño	67
Norte Santander	233
Putumayo	5
Quindío	37
Risaralda	12
Santander	66
Sucre	7
Tolima	39
Valle del Cauca	73

These results combined with the life expectancy at birth in each department allow obtaining the *YLL* as shown in Table 5-13 and its geographical distribution in Figure 5-12.

Table 5-13 *YLL* for selected departments in Colombia

Department	*YLL*
Antioquia	10,715
Arauca	230
Atlántico	221
Bogotá D. C.	12,281
Bolívar	188
Boyacá	3,896
Caldas	2,300
Caquetá	126
Casanare	296
Cauca	3,262
Cesar	183
Chocó	2,136
Córdoba	624
Cundinamarca	2,033
La Guajira	290
Huila	3,010
Magdalena	2,145
Meta	1,216
Nariño	2,879
Norte Santander	9,887
Putumayo	226
Quindío	1,517
Risaralda	509
Santander	2,822
Sucre	312
Tolima	1,615
Valle del Cauca	3,094

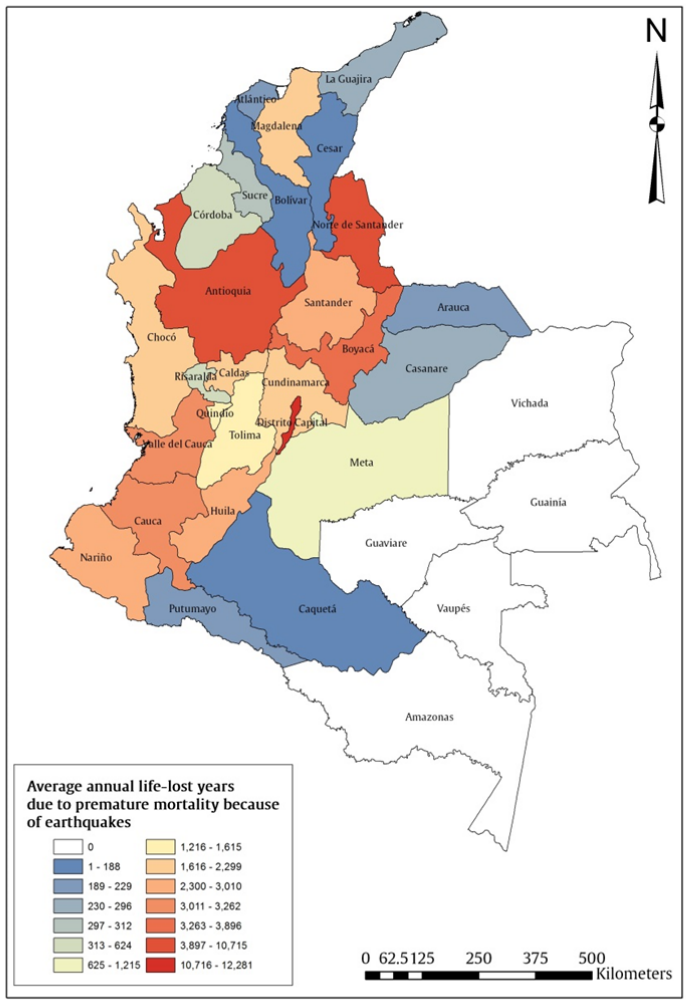


Figure 5-12 Average *YLL* because of earthquakes in Colombia

Considering only the YLL_i of the working age group, the GDP per capita and the unemployment rate, it is possible to obtain the average annual lost production due to premature mortality because of earthquakes as shown in Figure 5-13. Because of its seismic hazard level, population density and high GDP per capita, the Capital District has the largest value among the analysed units, followed by Antioquia and Norte de Santander.

Table 5-14 GPD per capita and working age YLL for selected departments in Colombia

Department	GDP per capita (USD)	Working age *YLL*
Antioquia	$ 4,982	6,503
Arauca	$ 7,451	108
Atlántico	$ 3,721	130
Bogotá D. C.	$ 7,578	7,743
Bolívar	$ 4,614	105
Boyacá	$ 5,092	2,200
Caldas	$ 3,445	1,368
Caquetá	$ 2,269	64
Casanare	$ 15,335	159
Cauca	$ 2,708	1,826
Cesar	$ 4,354	97
Chocó	$ 2,070	1,011
Córdoba	$ 2,466	337
Cundinamarca	$ 4,566	1,175
La Guajira	$ 2,882	143
Huila	$ 3,777	1,670
Magdalena	$ 2,488	1,106
Meta	$ 15,206	678
Nariño	$ 2,095	1,622
Norte Santander	$ 2,863	5,581
Putumayo	$ 4,315	117
Quindío	$ 3,174	907
Risaralda	$ 3,565	303
Santander	$ 8,515	1,712
Sucre	$ 2,225	173
Tolima	$ 3,630	905
Valle del Cauca	$ 4,864	1,910

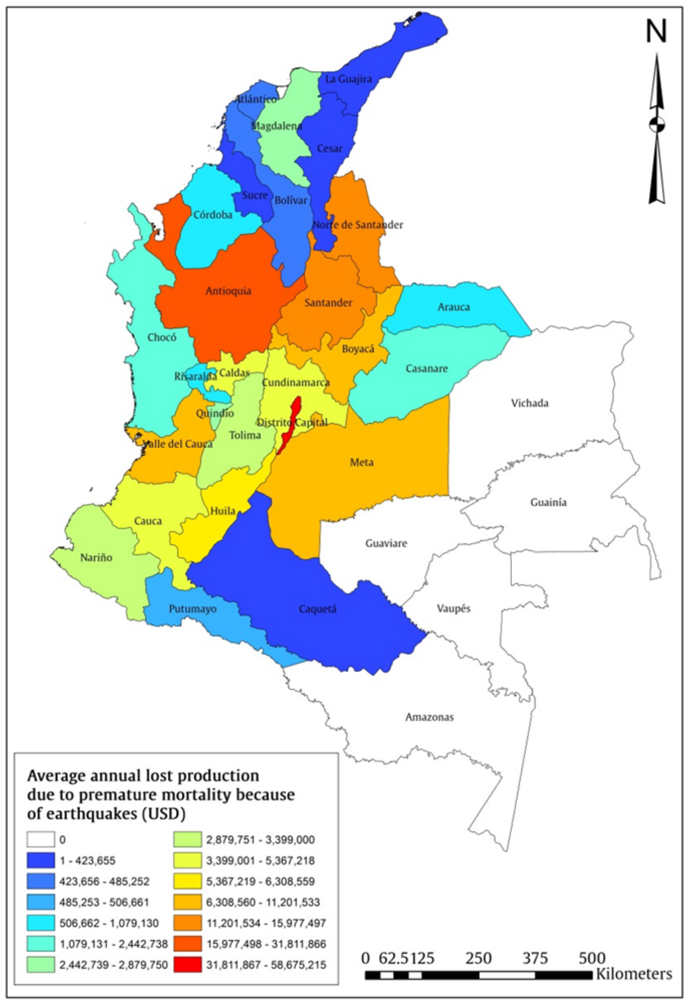


Figure 5-13 Average annual lost production due to premature mortality because of earthquakes in Colombia

Table 5-15 shows the obtained value as well as that obtained for the physical risk assessment and the ratio between these two figures. This last value is also shown in a graphical way in Figure 5-14.

Table 5-15 Summary of physical and human losses for selected departments in Colombia

Department	AAL (USD)	Average annual lost production (USD)	Ratio (%)
Antioquia	$ 1,752,000,000	31,811,866	1.82
Arauca	$ 13,900,000	806,679	5.80
Atlántico	$ 29,600,000	485,252	1.64
Bogotá D. C.	$ 3,070,000,000	58,675,215	1.91
Bolívar	$ 39,240,000	482,727	1.23
Boyacá	$ 141,300,000	11,201,533	7.93
Caldas	$ 220,000,000	4,712,006	2.14
Caquetá	$ 21,150,000	146,328	0.69
Casanare	$ 8,300,000	2,442,738	29.43
Cauca	$ 357,000,000	4,945,846	1.39
Cesar	$ 35,000,000	423,655	1.21
Chocó	$ 47,900,000	2,092,253	4.37
Córdoba	$ 114,300,000	831,605	0.73
Cundinamarca	$ 180,010,000	5,367,218	2.98
La Guajira	$ 11,700,000	411,346	3.52
Huila	$ 130,700,000	6,308,559	4.83
Magdalena	$ 43,200,000	2,752,357	6.37
Meta	$ 24,900,000	10,313,967	41.42
Nariño	$ 145,800,000	3,399,000	2.33
Norte Santander	$ 187,100,000	15,977,497	8.54
Putumayo	$ 15,500,000	506,661	3.27
Quindío	$ 181,400,000	2,879,750	1.59
Risaralda	$ 145,900,000	1,079,130	0.74
Santander	$ 317,300,000	14,574,401	4.59
Sucre	$ 42,500,000	384,550	0.90
Tolima	$ 174,700,000	3,284,502	1.88
Valle del Cauca	$ 459,900,000	9,288,251	2.02

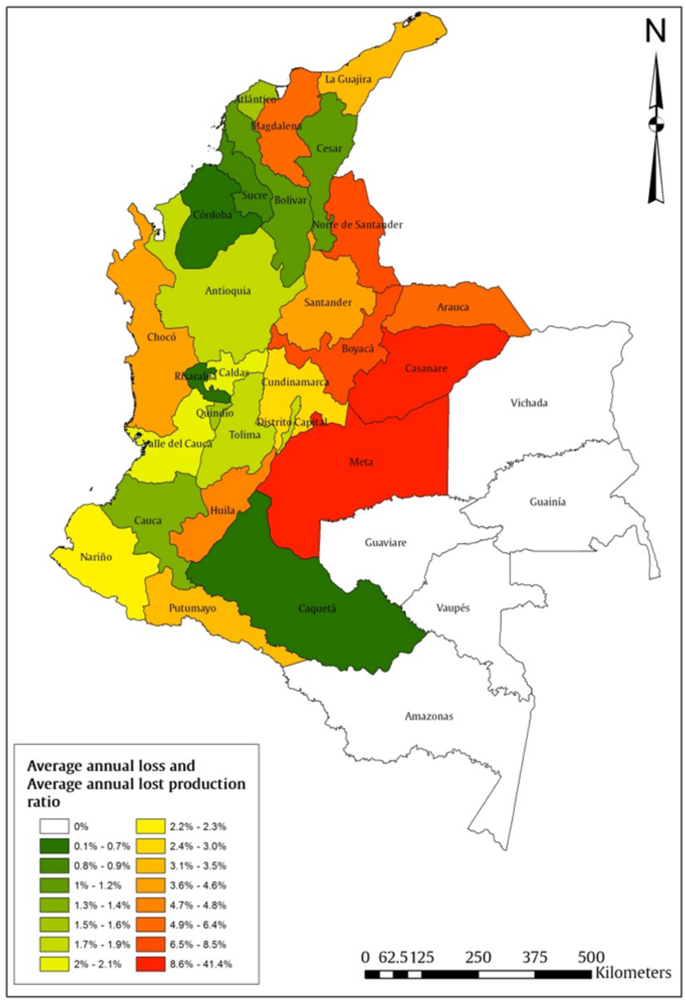


Figure 5-14 Human stock and physical stock ratio for Colombia

Subnational analyses provide more detailed information which can be useful at a national governmental level. If more detailed data in terms of exposure and hazard (mainly by considering local site effects) are available, higher resolution risk assessments can be developed at urban level, as presented in the next section. At subnational level, with a coarse-grain exposure database and a PSHA which only accounts for the bedrock level, Bogotá D.C. is suggested to invest approximately USD 60 million in seismic safety, a value that is expected to threefold when the effects of the soft soil deposits present in the city are considered (Bernal, 2014).

5.7 Application of the methodology at urban level

The proposed methodology is applied at urban level in Medellín, Colombia, a city that has more than two million inhabitants and is located on an intermediate seismic hazard zone with peak ground accelerations (PGA) of 0.15g associated to a mean return period of 475 years (AIS, 2010; Salgado-Gálvez et al., 2010). The city has complete and high quality information regarding the input data required for the analysis and the results are presented herein.

For this study, the seismic hazard model corresponds again to the most up to date study available for Colombia (Salgado-Gálvez et al., 2015c). The building by building exposure database is the one developed by Salgado-Gálvez et al. (2014) where each entry has information about the income level, building class and human and capital exposed value. Data for life expectancy at birth, projected population to 2015 and distribution of it in 5-years age ranges was obtained from the Colombian statistics department – DANE at county level and aggregated using the number of inhabitants as a weighting factor.

The estimation of *AAD* is performed in the public and private building stock that has more than 240,000 dwellings with different structural characteristics whose details can be found in Salgado-Gálvez et al. (2014b). Urban population projected for year 2015 is equal to 2,218,192 inhabitants (DANE and Alcaldía de Medellín, 2010) and is distributed by buildings considering their main use and based on official population density data. As in the previous case studies, an occupation level of 60% has been assumed.

An important difference in terms of input data for this case study is the consideration of the dynamic soil response by means of spectral transfer functions according to the zonation proposed by SIMPAD et al. (1999). In all cases, the transfer functions have values higher than 1.0 and, therefore, an amplification of the hazard intensities occurs for all spectral ordinates.

AAD is estimated in 541 people for Medellín which, in relative terms, corresponds to 0.25‰ of the total population count. As expected, higher values are expected for middle and high rise reinforced concrete buildings of medium and high-rise if compared to the non-engineered low-rise structures made of wood and zinc that do not cause as many deaths in case of collapse.

Based on the official demographic information (DANE and Alcaldía de Medellín, 2010), age distribution by 5 year span ranges is available as shown in Table Table 5-16.

Table 5-16 Population and age distribution for Medellín

Age range	Number of inhabitants	Relative number of inhabitants
0 to 4	127,152	5.7%
5 to 9	131,189	5.9%
10 to 14	132,672	6.0%
15 to 19	151,863	6.8%
20 to 24	169,467	7.6%
25 to 29	182,798	8.2%
30 to 34	168,471	7.6%
35 to 39	147,581	6.7%
40 to 44	130,319	5.9%
45 to 49	168,822	7.6%
50 to 54	181,808	8.2%
55 to 59	158,137	7.1%
60 to 64	125,673	5.7%
65 to 69	92,907	4.2%
70 to 74	58,501	2.6%
75 to 79	43,606	2.0%
80+	47,226	2.1%
TOTAL	**2,218,192**	**100%**

With this information, it is now possible to estimate AAD_i which is presented in Table 5-17. As explained, the sum of the AAD_i corresponds to the overall *AAD*.

Table 5-17 *AADi* for Medellín

Age range	*AADi*
0 to 4	31
5 to 9	32
10 to 14	32
15 to 19	37
20 to 24	41
25 to 29	45
30 to 34	41
35 to 39	36
40 to 44	32
45 to 49	41
50 to 54	44
55 to 59	39
60 to 64	31
65 to 69	23
70 to 74	14
75 to 79	11
80+	12
TOTAL	541

For administrative purposes, Medellín is divided into 16 counties (*comunas*) that have similar geographical extension but different socioeconomic characteristics. Since life expectancy at birth corresponds to a metric that has different values even when considering the same urban centre because of social, safety and public health issues, available data are disaggregated, in this case at county level. Since the main objective of the proposed methodology is to make an estimation of the cost associated to the lost productivity due to premature mortality, a unique value is needed for the city. For that reason, based on the number of inhabitants in each county shown in Table 5-18, a weighted average of the life expectancy at birth estimated in 76.96 years has been calculated.

Table 5-18 Population and life expectancy at birth at county level for Medellín

County	Life expectancy at birth	Population	% Population
Popular	74.98	130,369	5.9%
Santa Cruz	76.04	111,452	5.0%
Manrique	75.52	159,658	7.2%
Aranjuez	77.01	162,252	7.3%
Castilla	78.47	149,751	6.8%
Doce de Octubre	77.23	193,657	8.7%
Robledo	73.95	171,660	7.7%
Villa Hermosa	76.36	137,527	6.2%
Buenos Aires	75.75	136,774	6.2%
La Candelaria	75.83	85,505	3.9%
Laureles Estadio	79.09	122,243	5.5%
La América	78.82	96,278	4.3%
San Javier	73.82	138,063	6.2%
Poblado	81.69	128,839	5.8%
Guayabal	78.58	97,470	4.4%
Belén	78.99	196,694	8.9%

At this stage it is possible to estimate the YLL_i of earthquakes as shown in Table 5-19 which, as expected, shows lower values for advanced ages if compared with younger ones.

Table 5-19 YLL_i for Medellín

Age range	*YLLi*
0 to 4	2,309
5 to 9	2,223
10 to 14	2,086
15 to 19	2,202
20 to 24	2,251
25 to 29	2,205
30 to 34	1,827
35 to 39	1,420
40 to 44	1,095
45 to 49	1,213
50 to 54	1,085
55 to 59	751
60 to 64	443
65 to 69	214
70 to 74	64
75 to 79	21
80+	-
TOTAL	**21,410**

Sum of the YLL_i equals the total number of years of life-lost due to premature mortality because the earthquakes (*YLL*) which in this case corresponds to 21,410. Because the highest age range (80+) exceeds the life expectancy at birth, it is not added to the final result. To estimate the cost at societal level in terms of lost future productivity, *YLL* only for ages between 15 and 64 years are consider whose value is equal to 14,493. That value is finally multiplied by the GDP per capita, which for the case of Medellín, has been established in US$11,466 (Brookings Institute, 2015). Average annual lost production corresponds to US$166,179,929 which is approximately 45.8% of the *AAL* that considers only direct damage to the building portfolio (Salgado-Gálvez et al., 2014b). Just as a figure to bear in mind for comparison purposes, in Bogotá, Colombia, around USD 200 million were invested in the retrofitting of some public schools during four years starting in 2004 which, in annualized terms, is significantly lower than the value obtained for a city with less than half its inhabitants, such as Medellín.

Chapter 6

ON THE CAPABILITY OF CAT-MODELS FOR ESTIMATING EARTHQUAKE LOSSES

6.1 The Lorca case

The May 2011 earthquake that stroke Lorca, associated to the Alhama de Murcia fault which extends for more than 100 km with an inverse focal mechanism, although having a moderate magnitude, caused several casualties (9 death and more than 300 injured) besides important structural damage that did not allow more than 10,000 people to return to their homes and jobs. Also, two hospitals were evacuated because of severe structural damage that threatened patients and medical staff. The earthquake led to a chaotic situation in the post-earthquake phase because no previous experience in the implementation of an emergency plan existed (Barbat et al., 2011a).

According to the official damage survey conducted by the local administration (*Ayuntamiento de Lorca*), 19% of the buildings were not inspected since, at first sight, they only had minor damage. 52% of the inspected buildings were classified as habitable because of the lack of important damages, 16% of the inspected buildings were classified with restricted access since no structural damage occurred but non-structural elements were affected, 9% of the inspected buildings were classified with prohibited access because high structural damage levels were observed and finally, for 4% of the inspected buildings a demolition order was issued (Ayuntamiento de Lorca, 2012).

Insured losses, mostly related to residential and commercial units, reached almost €490 million (CCS, 2012). Although it is clear that the figure does not correspond to the whole direct damage cost of the earthquake in Lorca, since not all the underwritten property insurance policies have the same conditions and there are particular deductible and limit conditions on each of them, it can be used as a reference order of magnitude for the physical loss.

Regarding the characteristics of the observed damage, it can be said that many shear stress damages were observed in masonry units that constitute a vast majority of the building stock in Lorca. For reinforced concrete dwellings, damage associated to façades and division walls (mainly built with brick masonry) was commonly observed but, also, in waffled-slab buildings, damage associated to shear stresses occurred. Finally, damages due to the presence of short columns were observed in the reinforced concrete dwellings and, even more, the only building that collapsed as a consequence of the earthquake, reached that collapse state because of that effect.

This chapter presents a comparison between the observed damage after the earthquake, according to the official post-event damage survey, and the damage results obtained by using the proposed probabilistic risk assessment methodology considering an event with characteristics (magnitude, depth and location) similar to those of the 11th of May 2011 earthquake. This comparison aims to show that CAT-models are useful for estimating damages, losses and casualties for a large group of assets exposed to earthquakes. The amount of available information regarding this event constitutes a very good chance to develop said comparisons. The performed comparison can be summarized in the following four stages:

1. Perform a PSHA; from the final set of stochastic earthquakes, an event with similar characteristics in terms of magnitude, depth and location is identified. Hazard intensities in terms of acceleration were calculated for 23 spectral ordinates ranging from 0.0s to 2.3s. Full details about this PSHA are included in Annex 1.
2. Development of an exposure database which includes information in terms of location, structural system, age, number of stories, number of inhabitants and replacement cost for the buildings within the urban area of Lorca. A total of 17,064 dwellings were included in the exposure database developed and a dwelling by dwelling resolution level was used.
3. Assignment of vulnerability functions to the identified building classes of Lorca. A total of 22 vulnerability functions were used. The vulnerability functions in this comparison account for the physical and human loss dimensions.
4. Probabilistic damage and loss assessment for the chosen event. Results are obtained in terms of *MDR* which can be converted into monetary units based on the replacement cost of each dwelling. Additionally, the expected number of deaths associated to indoor mortality due to building collapse is obtained.

6.2 Seismic hazard scenario

Figure 6-1 shows the shakemap, in terms of peak ground acceleration (PGA), for the selected event which is associated to the *ESAS250* seismogenetic source (Woessner et al., 2015) that is located beneath the city of Lorca. The shown seismic hazard intensities are computed at bedrock level.

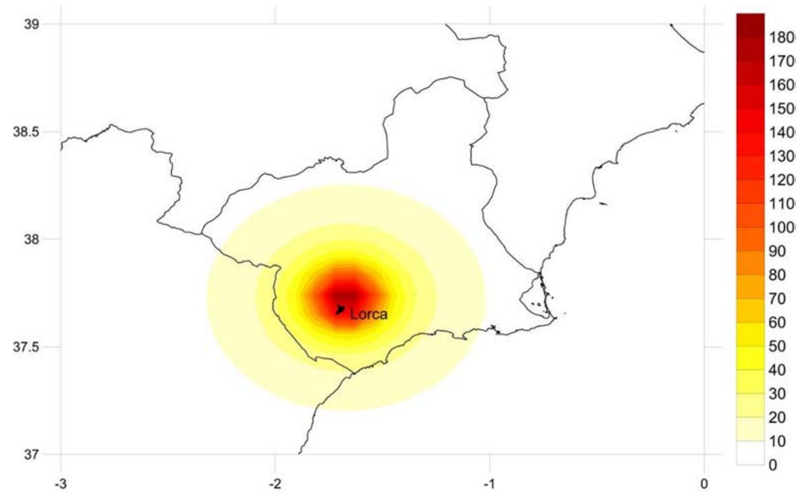


Figure 6-1 Shakemap (PGA) for the selected event (cm/s^2)

According to the requirements of probabilistic loss assessments, for each spectral ordinate both the expected value and the dispersion of the hazard intensity measures (i.e. spectral accelerations) are calculated. This modelled event, like the real one, has a magnitude of 5.1 and the PGA similar to the recorded one in the city of Lorca at bedrock level.

6.3 Exposure database

For the probabilistic risk assessment, an exposure database that considers the public and private building stock within the urban area of Lorca is developed. A detailed building by building resolution level was chosen since the required information was available and also since the results of the post-earthquake damage survey are reported at this same scale. The process of developing exposure databases has always presented challenges in risk modelling since usually the required information is not available directly from a unique source and, in many cases, it needs to be inferred or generated through a set of indexes obtained from several sources. In this case, information about the geographical location and structural characteristics such as age, material, structural system, number of stories, replacement cost, number of occupants and building class is required for each element. Those parameters were assigned to each of the elements included in the final database using the data and procedure explained in the following. For the human occupation value, based on the latest census data the total population of the urban area of Lorca (59,523 people) was uniformly distributed using the total constructed area as a reference parameter. When conducting a probabilistic seismic risk analysis, one of the big assumptions involved in the process is related to the law of large numbers, that is, a large set of elements are to be included in the database for the final results to be statistically significant; thus, even if over or under estimation errors are expected, they tend to be compensated at the end of the process.

Updated cadastral data are available for Lorca (MHAP, 2013) with a building by building resolution level. Since the information was generated for cadastral and tax purposes, several properties, other than buildings, such as terraces, squares and balconies are included. After a depuration process, with the objective to include only the buildings, 17,017 elements remained. During this depuration process, the buildings classified as ruins (before the occurrence of the 2011 earthquake) by the cadastral office were also removed. The cadastral information contains data about the geographical location and number of stories of each building. Building footprints were compared with an updated aerial image of Lorca (ESRI, 2010) and additional elements were included in the database, ending with a total of 17,064 buildings. Figure 6-2 shows the map with the buildings in Lorca according to the number of stories attribute. As it can be clearly seen, most of the buildings in Lorca are classified as low-rise from a structural point of view (i.e., buildings with 1 to 3 stories).

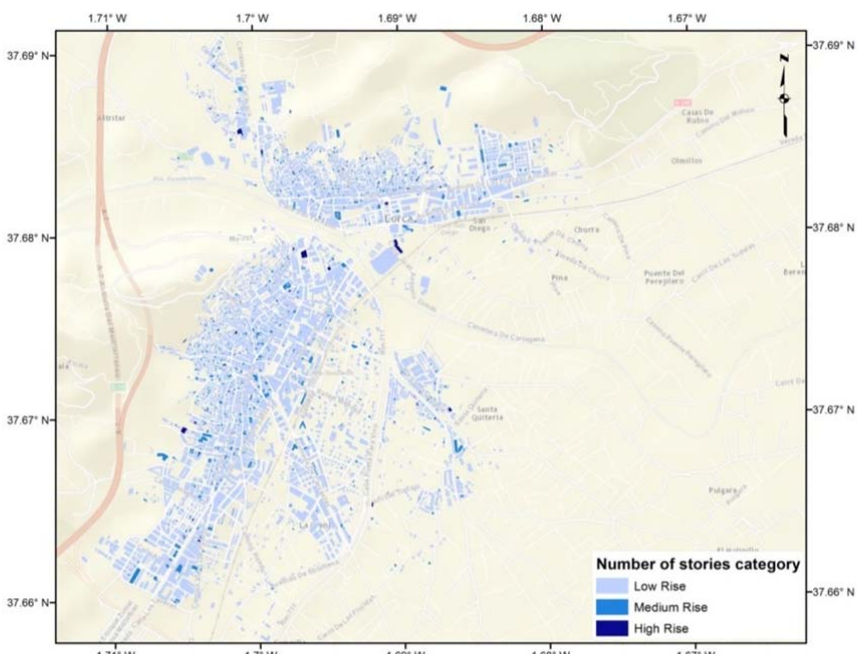


Figure 6-2 Number of stories category for the building portfolio of Lorca

From the most recent Spanish population and housing census (INE, 2011), it is possible to define the age distribution of the buildings in Lorca which is summarized in Table 6-1.

Table 6-1 Age distribution for the buildings in Lorca

Age	Distribution (%)
Before 1900	4.44
1900-1920	2.75
1921-1940	4.02
1941-1950	4.81
1951-1960	11.13
1961-1970	13.46
1971-1980	19.36
1981-1990	13.26
1991-2001	13.14
2002-2011	13.62

Based on previous studies (Benito et al., 2005) and making use of the age distribution, a vulnerability classification based on the EMS-98 scale (Grünthal, 1998) using the data of Table 6-2 was developed. It can be seen from Table 6-2 that structures are classified in categories between A and D on this scale. Figure 6-3 shows the geographical distribution of the vulnerability classes for the buildings of Lorca, where the historical centre of the city can be clearly identified.

Table 6-2 Vulnerability class distribution by construction date for the buildings of Lorca

	EMS98 vulnerability class	A	B	C	D
Age	Before 1900	80%	20%	-	-
	1900-1920	72%	28%	-	-
	1921-1940	72%	28%	-	-
	1941-1950	69%	28%	3%	-
	1951-1960	46%	49%	5%	-
	1961-1970	18%	38%	44%	-
	1971-1980	5%	40%	55%	-
	1981-1990	-	38%	57%	5%
	1991-2001	-	28%	62%	10%
	2002-2011	-	18%	69%	13%

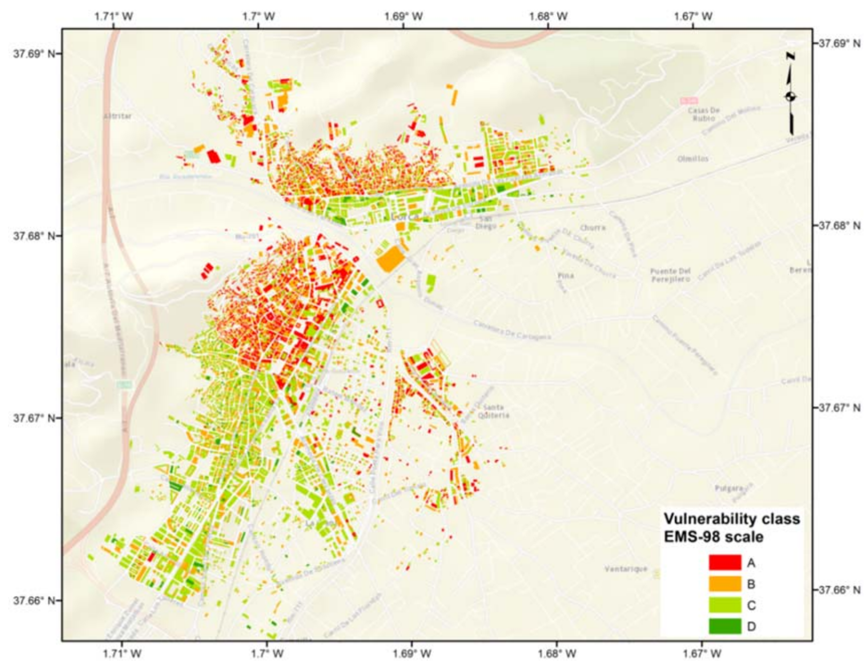


Figure 6-3 Spatial distribution of the vulnerability classes for the buildings of Lorca

No cadastral price information was available in the database and, for that reason, an index based on the total constructed area was obtained to capture the replacement cost of each element. The replacement cost is intended to capture the repair or replacing cost of the buildings to bring them to exactly the same conditions which were used for their characterization. The main objective of this appraisal is to establish an order of magnitude for the replacement cost of the buildings within the urban area of Lorca as a whole. In this case, replacement costs do not take into account historical or heritage values of the structures.

Based on INE (2011), a base value of €1,247 per constructed square meter was established for the city; in addition to this, and in order to take into account the fact that all elements do not have the same price, age was selected as a differentiation parameter. Since repairing stone and brick masonry buildings is more expensive than repairing reinforced concrete buildings due to the necessity of specialized manpower, a factor that increases with the age was defined (see Table 6-3).

Table 6-3 Replacement cost factor index by construction date

Age	Age factor	Cost per constructed m2
Before 1900	2.00	2,494 €
1900-1920	2.00	2,494 €
1921-1940	1.75	2,182 €
1941-1950	1.75	2,182 €
1951-1960	1.50	1,871 €
1961-1970	1.50	1,871 €
1971-1980	1.50	1,871 €
1981-1990	1.25	1,559 €
1991-2001	1.25	1,559 €
2002-2011	1.00	1,247 €

By having defined the age and vulnerability class distribution, several building classes were identified from the information collected by Benito et al. (2005). A vulnerability class according to the EMS-98 scale has been assigned to each building class. Buildings in Lorca are mostly made of different types of masonry (bricks and stone) for the low-rise structures while for medium and high-rise buildings reinforced concrete (R/C) waffled slab buildings are mostly used. Steel frames and prefabricated R/C structures are found mostly in the industrial facilities of the city.

By combining the above mentioned two parameters for all the elements, a building class was assigned to each dwelling and a total of 10 building classes were identified for the analysis. Table 6-4 shows the building classes which were identified and assigned in Lorca. In the second column an abbreviation code is included whereas in the third column the classification according to the EMS-98 vulnerability scale is shown. Figure 6-4 shows the geographical distribution of the building classes of Lorca.

Table 6-4 Identified building and vulnerability classes in Lorca

Building class	Abbreviation code	Vulnerability class (EMS-98)
Stone masonry	M-PP	A
Earthen	M-TA	A
Toledo masonry	M-ET	B
Brick masonry	M-L	B
Masonry walls and R/C slabs	M-H	C
Pre 1995 R/C frames	E-H	C
Post 1995 R/C frames	E-H2	D
R/C frames with steel braces	E-HX	D
Prefabricated R/C structures	E-HF	C
Steel buildings	E-MT	D

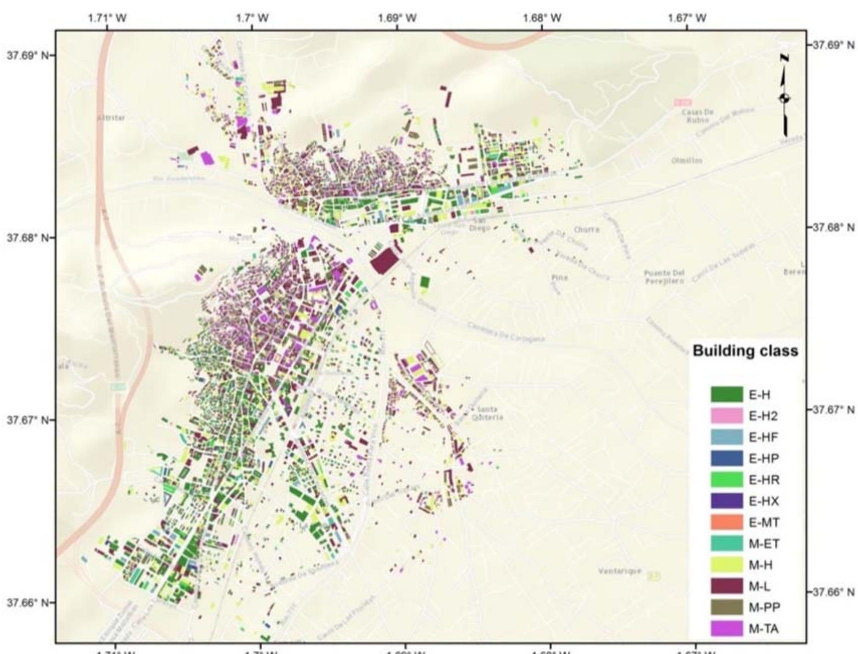


Figure 6-4 Building class distribution for Lorca

Table 6-5 shows a summary of the exposed assets in terms of building classes, number of elements and replacement costs of each of them from where it can be clearly seen that most of the buildings in Lorca are made of masonry, concentrating more than 60% of the total both in number and in exposed value. Moreover, waffle slab buildings constitute the majority of the R/C structures in Lorca (more than 20% of the buildings in the city).

Table 6-5 Summary of exposed assets statistics

Building class	Number of dwellings	% of dwellings	Exposed value (million €)	% of exposed value
Stone masonry	1,838	10.8	848	12.2
Earthen	1,955	11.5	978	14.1
Toledo masonry	528	3.1	203	2.9
Brick masonry	5,207	30.5	2,057	29.7
Masonry walls and R/C slabs	2,963	17.4	1,156	16.7
Pre 1995 R/C frames	3,432	20.1	1,293	18.7
Post 1995 R/C frames	485	2.8	161	2.3
R/C frames with steel braces	35	0.2	8	0.1
Prefabricated R/C structures	593	3.5	216	3.1
Steel buildings	28	0.2	8	0.1
TOTAL	**17,064**	**100**	**6,928**	**100**

6.4 Physical vulnerability functions

Vulnerability functions describe the variation of the first two probability moments of loss with respect to the hazard intensity which, again in this case, are spectral accelerations. A Beta probability distribution function is assigned to them as mentioned before and, in this case, the mean value and the standard deviation correspond to the mentioned probability moments. Once this distribution function is computed, all the parameters required to compute risk, in a probabilistic way, are available (Ordaz, 2000). Each of the building classes has associated a unique vulnerability function. The replacement cost of each asset is needed to quantify the expected losses in monetary units since what it is obtained at each intensity level is the ratio of the repair cost relative to the total value of the building and the same applies for the occupation level considered at each dwelling.

Structures with different characteristics behave and might be damaged in a different way when subjected to the lateral forces imposed by the same event and, therefore, hazard intensities for different spectral ordinates are calculated. This difference in the behaviour of the buildings can be accounted using the fundamental period of each building class. Each vulnerability function has also associated an spectral ordinate that corresponds to the typical elastic fundamental period of the building class whose expected damage is being characterized, establishing the link between the vulnerability functions and the building classes.

A total of 22 vulnerability functions were used in the analysis, which have been developed for the Global Risk Model (Cardona et al., 2014) and included in the Global Assessment Report on Disaster Risk Reduction 2013 (UNISDR, 2013). Figure 6-5 shows the different vulnerability functions used herein from where it is clear that some building classes, especially those made of unreinforced masonry, are far more vulnerable in seismic terms than others, having for the same intensity level a higher associated *MDR*. The codes of Table 6-4 are used to denote the vulnerability functions, and the height of the structures is included in the analysis through three different categories: low-rise (L) for buildings between 1 and 3 stories, medium-rise (M) for those that have 4 to 7 stories and high-rise (H) for 8 and more. These abbreviations are also included in the notation used in Figure 6-5.

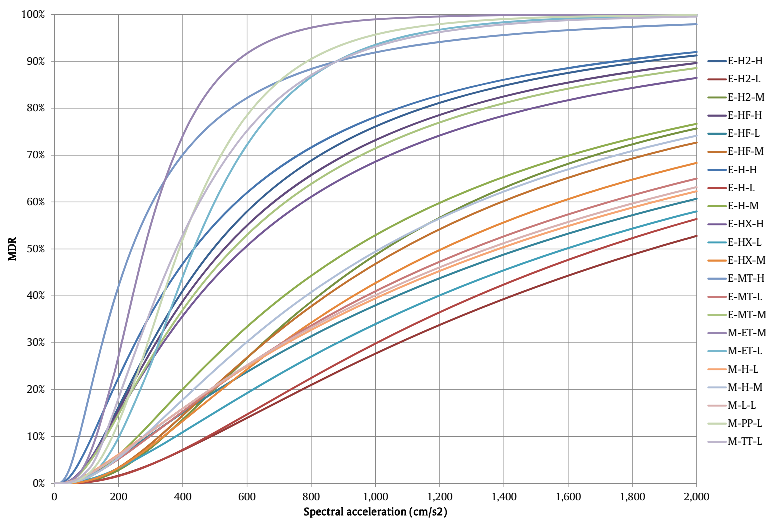


Figure 6-5 Physical vulnerability functions used for the buildings in Lorca (L=Low rise; M=Medium rise; H=High rise)

6.5 Human vulnerability functions

With the objective modelling and comparing the number of deaths calculated with the proposed model, when the selected event occurs, with the real data, a set of vulnerability functions, considering the human loss dimension, were developed. These functions were developed using the methodology explained in Chapter 5, starting from the physical vulnerability ones. In this case, loss is not expressed in terms of the *MDR* but of the *LR* and these values are defined according to the construction material and number of stories. Figure 6-6 shows the human vulnerability functions developed to model deaths because of earthquakes in Lorca. Again, the same abbreviation codes shown in Table 6-4 are used.

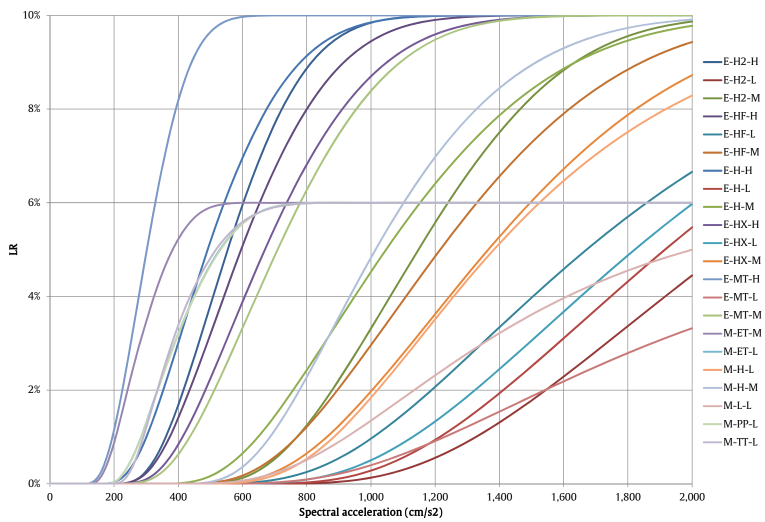


Figure 6-6 Human vulnerability (deaths) functions used for the buildings in Lorca (L=Low rise; M=Medium rise; H=High rise)

6.6 Comparison of modelled and observed damages, losses and deaths number

When a single event approach is selected as in this case, *N* takes a value equal to 1, while the frequency of occurrence, F_A is set to 1.0 in Equation 2.6. For the selected event, the intensities are first calculated for the area under analysis and, then, for each asset included in the exposure database, the loss and its variance are calculated (in both physical and human dimension) using the vulnerability functions associated to each asset (based on its geographical location and the hazard intensity value at each location). This process is repeated for the 17,064 buildings included in the exposure database. When the risk assessment is performed for a single hazard scenario, a deterministic approach is chosen for the temporal dimension of the hazard while a probabilistic approach still remains for the hazard intensity calculation, vulnerability representation and loss calculation.

For this scenario, around €615 million were obtained as losses, corresponding to 8.9% of the total exposed value. This value only considers the direct physical damage while other aspects, such as the historical, heritage and cultural values of the elements, are not included because they are out of the scope of this study. Table 6-6 shows the risk results in terms of the aggregated *MDR* for the considered building classes of Lorca; from this, it is clear that the masonry building classes concentrate the highest physical risk values. Furthermore, it can be seen that among the building classes with higher *MDR* are the earthen structures, which have proven to have poor performance under the seismic demand due to the poor construction practices, age, low maintenance and quality of the construction materials. Stone masonry structures have the highest *MDR* values, showing the fact that the stone masonry buildings present the highest risk. R/C slabs also have an important contribution to the modelled losses due to their high seismic vulnerability related to the structural typology and the conceptual design errors.

Table 6-6 Modelled damage and *MDR* by building class

Building class	Damage (million €)	MDR (%)
Stone masonry	108.5	12.8
Earthen	157.5	16.1
Toledo masonry	33.4	16.5
Brick masonry	159.3	7.7
Masonry walls and R/C slabs	97.6	8.4
Pre 1995 R/C frames	40.1	3.1
Post 1995 R/C frames	1.3	0.8
R/C frames with steel braces	0.4	4.9
Prefabricated R/C structures	16.1	7.4
Steel buildings	0.5	6.1
TOTAL	**614.7**	**8.9**

Besides obtaining a gross value of the expected losses, this analysis allows disagregating the results in several categories (as many as the ones included in the exposure database). Since the risk assessment has been performed on a geo-referenced database, it is possible to obtain the geographical distribution of the expected losses and damages in terms of *MDR* for the exposed assets in Lorca as shown in Figure 6-7. From here, it can be seen that, according to the model, the most affected dwellings are located within the historical centre and in the northern part of Lorca which is also an area with old structures.

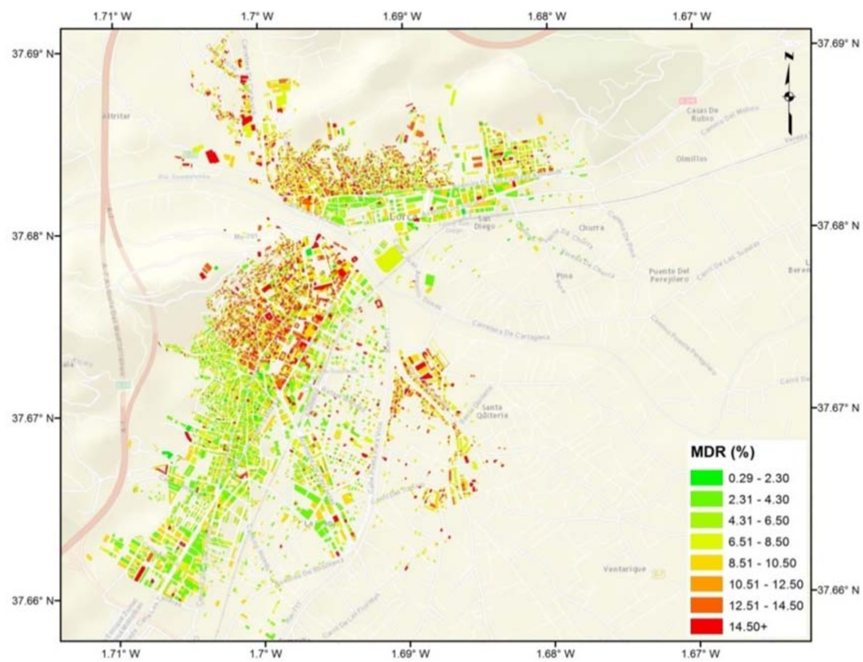


Figure 6-7 Modelled *MDR* (%) for the considered scenario in Lorca

According to the damage survey performed by the Ayuntamiento de Lorca (2012), the damaged buildings were classified in the following four categories:

1. Habitable (green)
2. Restricted access because of damage on non-structural elements (yellow)
3. Prohibited access because of structural damage requiring repairing and retrofitting measures (red).
4. Mandatory demolition order (black)

A total of 7,852 buildings were inspected, accounting for approximately 44% of the buildings within the urban area of Lorca. It was observed that 19% of those did not suffer any significant damage. The distribution of recorded damage among the four categories is shown in Table 6-7.

Table 6-7 Recorded damage statistics and categories for the Lorca earthquake

Damage category	Number of buildings	% of buildings
No damage	1,492	19.0
Habitable	4,083	52.0
Non-structural damage	1,256	16.0
Structural damage - forbidden access	707	9.0
Demolition order	314	4.0
Total damaged buildings	**7,852**	**100**

These results have the same order of magnitude as other damage surveys conducted in the city by other experts and institutions for the same event (Barbat et al., 2011b; IGN et al., 2011; Benito et al., 2012; Menéndez et al., 2012; Álvarez et al., 2013). The damage survey was also geo-located and the damage map shown in Figure 6-8 is available online (Ayuntamiento de Lorca, 2012). The number of inspected buildings can be considered as statistically significant and, thus, useful for establishing damage distributions and defining damage categories along the city.

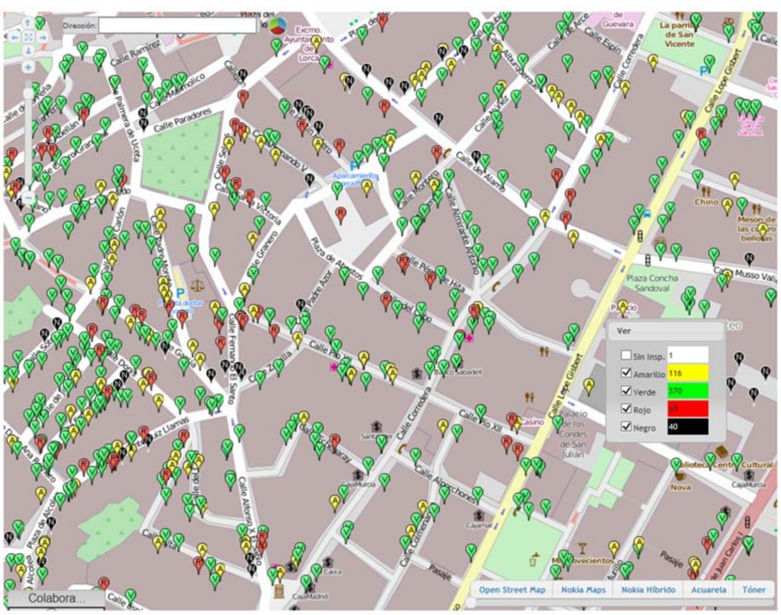


Figure 6-8 Online post-earthquake damage survey database for Lorca

In order to compare the observed with the simulated damage, *MDR* ranges were set to represent the different damage categories. It is assumed that buildings need a demolition order if *MDR* is higher than 50%; have forbidden access if *MDR* is between 16 and 49.9%; have restricted access if *MDR* is between

10 and 15.9%; are habitable if *MDR* is between 4 and 9.9%; and have no damage if *MDR* is lower than 4%. According to these levels, the statistics for all buildings in Lorca is presented in Table 6-8.

Table 6-8 Modelled *MDR* and damage categories for the scenario in Lorca

Damage category	MDR (%)	Number of dwellings	Dwellings share (%)
No damage	0.0 - 3.9	2,163	12.7
Habitable	4.0 - 9.9	6,306	37.0
Non-structural damage - restricted access	10.0 - 15.9	8,067	47.3
Structural damage - forbidden access	16.0 - 49.9	528	3.1
Demolition order	50.0+	0	0.0
TOTAL		**17,064**	**100.0**

The percentage values of the simulated scenario are similar for all the damage categories presented in Table 6-7 with the exception of the buildings with demolition order. Figure 6-9 shows the simulated results grouped into the damage categories defined by the local authorities of Lorca during the post-event damage survey.

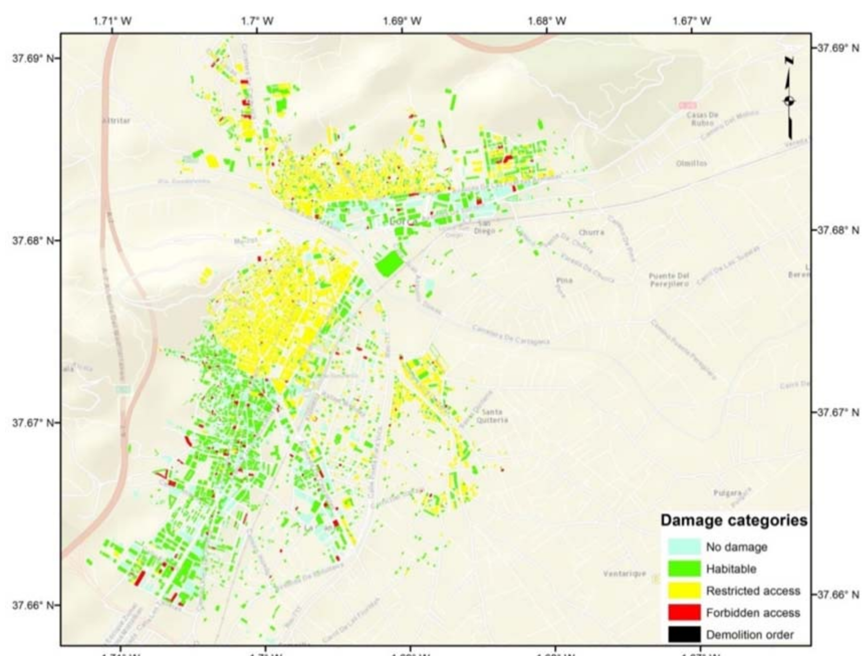


Figure 6-9 Modelled damaged categories for the considered scenario in Lorca

In terms of lethality, it is important to clarify that all 9 deaths reported after the earthquake occurred outdoors due to falling objects and, therefore, under the assumption and limitations used in this thesis for the development of the human vulnerability functions, the indoor mortality due to building collapse for the Lorca earthquake is 0. Nevertheless, it is important also to remember that the event that caused most damages and the collapse of a building was preceded by a smaller one, some hours before, which warned the inhabitants and made them leave the structures. This is reflected in a very low occupation rate which has been acknowledged as the main reason for a lower death toll (Barbat et al., 2011a).

Table 6-9 shows the expected deaths by building class obtained from the simulation in Lorca. Three different occupation values were considered and their results are shown herein. The first correspond to full occupation of the residential dwellings, which can be assumed to be a night-time scenario; the second to a 60% occupation rate of the residential dwellings which can be assumed as the one that, because of the day and time of the May 2011 earthquake, in case that there had not been a previous earthquake, would had been feasible in the city and, finally, a 10% occupation of the residential dwellings is also considered to reflect what can be assumed to be the occupation rate at the time of the earthquake but also considering the occurrence of the previous one hours ago. For the full occupation case, around 60 deaths are expected which, according to the damages observed in many structures, mainly in the centre and south of the city of Lorca, is considered as feasible. Anyhow, it is also important to highlight that the only structural collapse occurred in an empty Pre-1995 R/C frame and according to the simulation no casualties are expected for that building class. Clearly, if there had been occupants in that building that collapsed, the recorded death toll distribution had been completely different and larger.

Table 6-9 Modelled deaths for the scenario in Lorca by building class

Building class	Expected deaths		
	Full occupation	60% occupation	10% occupation
Stone masonry	22	13	2
Earthen	25	15	2
Toledo masonry	14	8	1
Brick masonry	0	0	0
Masonry walls and R/C slabs	0	0	0
Pre 1995 R/C frames	0	0	0
Post 1995 R/C frames	0	0	0
R/C frames with steel braces	0	0	0
Prefabricated R/C structures	0	0	0
Steel buildings	0	0	0
TOTAL	**61**	**37**	**6**

6.7 Prospective and fully probabilistic seismic risk assessment of Lorca

Even though the input data for the probabilistic risk assessment presented before was generated with the sole objective of performing the comparison of observed and modelled losses, they are the same for a prospective risk assessment, which can provide valuable information related to disaster risk management in terms of probabilistic metrics such as the *LEC*, *AAL* and *PML*. Because of that, it was considered of interest to make such estimation for Lorca and, to share the obtained results with the local community in different communications and events regarding urban resilience. Because a complete set of stochastic events was considered in this case, it is possible to express the risk results for Lorca in terms of the *LEC* as shown in Figure 6-10 (Salgado-Gálvez et al., 2015a). Since a Poissonian process was used for the estimation of losses, information on the *LEC* can be interpreted as the number of earthquakes per year (or in any given year) that produce the exceedance of a given loss value, *l*.

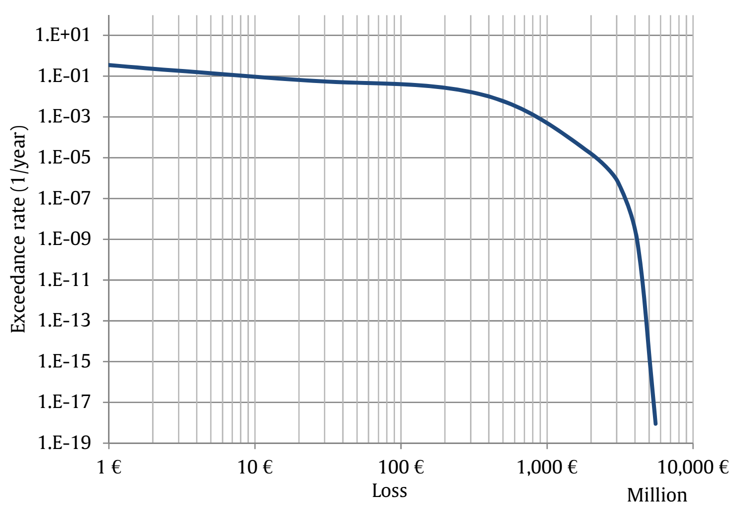


Figure 6-10 Earthquake *LEC* for Lorca

Table 6-10 shows a summary of the risk results in terms of the *AAL* and selected *PML*. A 2.4‰ relative *AAL* combined with relative *PMLs*, close to 10% of the total exposed value, correspond to a high seismic risk level. Figure 6-11 shows the *PML* plot for Lorca that, as explained before, contains exactly the same information as the *LEC* but arranged in a different way.

Table 6-10 Summary of seismic risk results for Lorca

Results		
Exposed value	EURx10^6	6,927.72
Average Annual Loss	EURx10^6	16.329
	‰	2.357
Probable Maximum Loss		
Return period	Loss	
Years	EURx10^6	%
100	393.37	5.68
250	568.50	8.21
500	689.83	9.96
1000	831.38	12.00

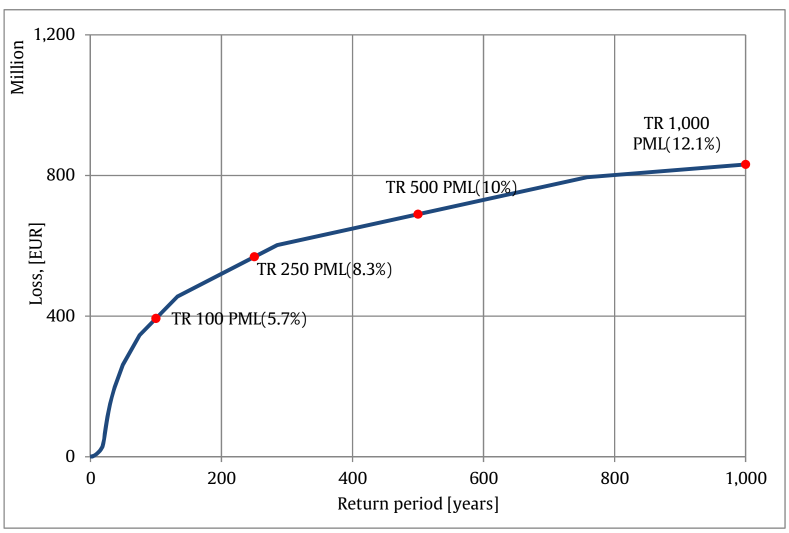


Figure 6-11 Earthquake *PML* plot for Lorca

As in the case of the single scenario assessment, risk maps can also be obtained for the fully probabilistic case. The best metric to represent seismic risk in graphical terms is the *AAL* in relative terms (see Figure 6-12) since it captures the elements with the highest risk level and not only the ones where the most expensive damages are expected to occur.

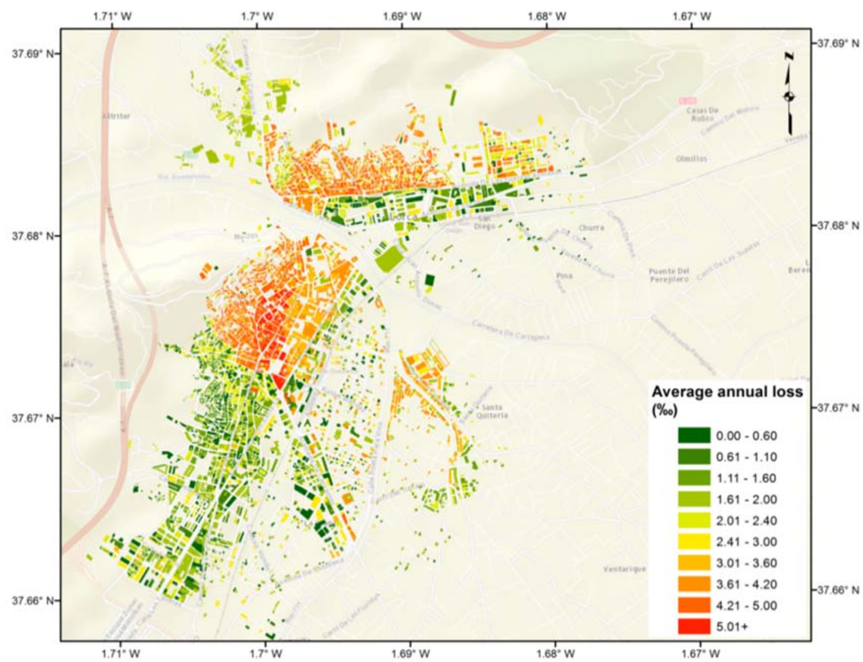


Figure 6-12 Average annual loss (relative) for the buildings of Lorca

When reliable information about the total constructed area is available, such in the case of Lorca, a combination between the physical risk results and this area can be obtained. In this case, the absolute *AAL* has been divided by the total constructed area of the dwellings and the geographical distribution of it is shown in Figure 6-13.

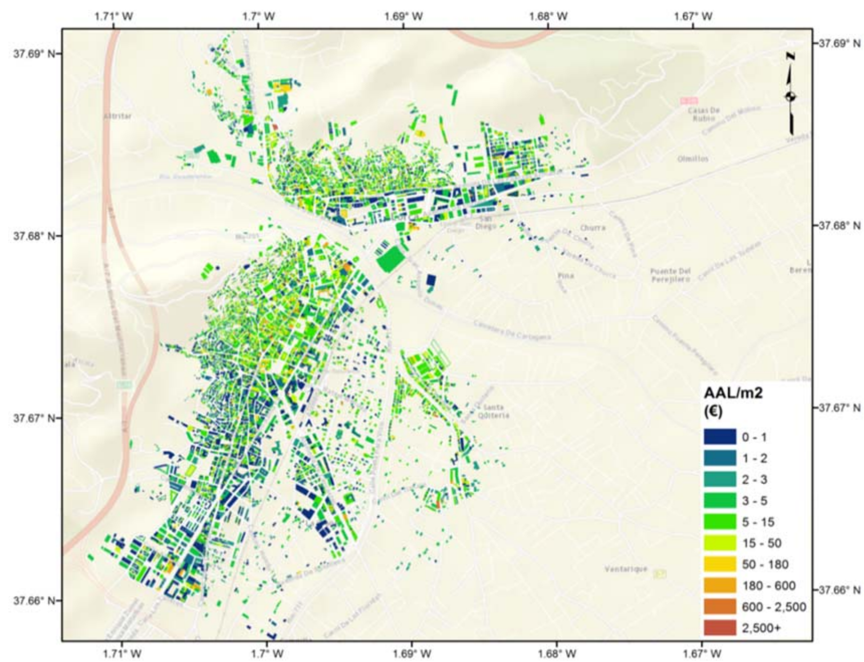


Figure 6-13 Average annual loss (absolute) per constructed square meter in Lorca

6.8 Final comments

Probabilistic risk assessments are intended to provide an order of magnitude of the expected losses and their average frequency of occurrence when a *LEC* is calculated, and not to predict the exact damage levels and their geographical location in the area under analysis.

After a disaster occurs, performing a good quantification of the losses is not an easy task and big challenges arise when trying to disaggregate the records and observations by categories. Double counting and the aggregation level have to do with the final recorded values (Cochrane, 2004). Specifically in the case of Lorca, defining and concluding that no damage (and loss) occurred to most of the building stock by a single and fast observation may not be sufficient for a rigorous comparison and, additional to the inherent limitations that the model has, this also needs to be considered while interpreting the final results.

Catastrophic events have low occurrence frequencies and, thus, there are no sufficient observed damage and loss records available which can be used in a comprehensive calibration process; coinciding in the order of magnitudes for a single observation may not be more than a coincidence. Also, those events have associated a power law and because of that, errors even two-folding what is being modelled and observed (or the other way round) can be considered as acceptable (Woo, 2011). Even if a CAT-model is adjusted to match the observed damage for a unique event, this does not guarantee the reliability for a different event with different characteristics at a different location. Finally, it is important to remember that no amount of observations can deny the possibility of a surprise (Woo, 2011) and that these models should not be blind trusted. A deep analysis of the underlying data quality and completeness, besides the selected methodology in terms of scope, assumptions and limitations, is required for a good interpretation of the final results. These last are far more important than the model bearing in mind that they can never be better than the data which they use.

Regarding the estimation of deaths for Lorca using the selected CAT-model, the real occupation rate at the moment of the event is still an unknown value and it is the reason for the consideration of different occupation scenarios. Even if the obtained values do not match with those recorded after the event, and the fact that the ones that occurred were outdoor, according to the type of damages in both structural and non-structural elements with a night-time scenario, the overall number of indoor deaths would had been higher and closer to the results obtained with the model used herein.

As a reflection of what happened in Lorca after the earthquake, it is important to mention that many buildings were not demolished because they presented a high level of damage and could not be retrofitted or repaired but due to social, institutional and property insurance reasons. This fact contradicts what has been found for cases where the destruction is not complete but extensive and where it is easier and cheaper to repair than to replace (Hallegate and Dumas, 2009). Nevertheless, it is important to remember that a catastrophic event, by destroying the most vulnerable elements, can somehow decrease the risk level whilst also the reconstruction process can represent an economic boost for the affected region and in the medium-long term lead to improvements in the economic performance from a macroeconomic perspective.

Even if today there are still many structures to be rebuilt in Lorca, the reconstruction process has used better construction practices and it is expected that the overall vulnerability of the new building stock is to decrease. This is a case where the reconstruction investment is expected to derive in a built stock with better quality than the lost one. Since a considerable number of elements were given a mandatory demolishing order, a future assessment considering the new (and in theory lower) vulnerability levels, should provide lower loss values than the presented in this study. Anyhow, these exercises allow assessing that the used methodology accounts in a proper way for the relevant uncertainties. Also, even if adjustments in a model are made following the observations of a real event, its calibration is only applicable to the region that was examined (Spence et al., 2003), an issue that has relevance given the global scope of said tools in today's world.

Chapter 7

CONCLUSIONS AND FUTURE RESEARCH

This last chapter presents the main conclusions derived from the methodology proposed on this thesis as well as from the results obtained in the case studies. Additionally, future research lines are identified accompanied by a brief overview for each of them.

Earthquakes will continue occurring in the future but that they become catastrophes or not, will depend not only in our understanding but also on how comprehensive, feasible and holistic DRR schemes are put into practice. For this last to become true, a technical based estimation of the minimum public investment on corrective actions regarding seismic safety with the objective or reducing earthquake mortality is an important and innovative contribution.

7.1 Conclusions on the use of CAT-models for estimating losses and casualties

CAT-models provide a robust and comprehensive framework for the probabilistic estimation of losses, in different of its dimensions, associated to the occurrence of low frequency and high impact natural events, such as earthquakes. Anyhow, it is important to be aware in advance of the assumptions in which they are built as well as on their scope, objectives and limitations.

Modelling risk is very different than understanding risk and therefore, CAT-models are not to be neither considered, nor used, by decision-makers but as tools that can provide valuable information to human beings to make them.

Even if, for the case study of Lorca, it was shown that the exact estimation and location of the damages and losses is not possible by using CAT-models, still their objective of providing order of magnitudes in terms of damages, casualties and economic losses, has been accomplished. At this stage, it is relevant to remember what Keynes once said: "*It is better to be roughly right than precisely wrong*" and in fields such as DRR these models provide very useful results supported by a robust methodology.

One important component of a comprehensive seismic risk assessment is the hazard analysis and, regarding this, the probabilistic seismic hazard analysis approach has proven to be complete and comprehensive providing robust results that can be used in several fields and in several ways. This thesis has shown how the results of a probabilistic seismic hazard analysis can be used for the simulation of a set of stochastic events to be used in fully risk assessments but, also, how they, if expressed in terms of hazard curves, can be used to simulate seismic hazard maps under different approaches such as the fixed mean return period, the optimum design and the uniform collapse probability. Even if the underlying methodology of the probabilistic seismic hazard analysis has not suffered significant changes from its original proposal in the late 1960's, the completeness and quality of the input data are still under continuous improvements mainly in the aspects related to the ground motion prediction equations.

The fact that the exact same probabilistic and prospective risk assessment methodology can be applied at different resolution levels also provides a very good opportunity for the development of risk identification processes with different purposes. For example, one starting point can be conducting coarse-grain assessments in order to raise risk awareness (such as the case of the UNISDR's GAR13 and GAR15) and, once stakeholders understand the underlying methodology and more detailed data are gathered and/or generated, risk assessments with higher resolution in terms of hazard and exposure can be developed with the objective of being used within a decision-making process.

7.2 Conclusions on seismic risk and sustainable development goals

In chapter 3, it was explained why earthquakes can be understood as economic shocks and, therefore, how they can be a real threat for sustainable development. The biggest challenge regarding earthquakes and sustainable development is the lack of appropriate and sufficient financial preparation for the required emergency attention and reconstruction efforts needed after the occurrence of an event. Even if in some cases this has occurred based on the proposal on risk neutrality for governments, the budgetary reallocation, when resources have been needed, has proven to be economically inefficient and in developing countries and Small Islands Developing States the theoretical benefits of geographical and economic diversification have not occurred.

Even in cases where a better economic performance has been observed after the occurrence of an earthquake, there is no evidence that disaster risk neutrality at governmental level has posed any significant economic advantage and/or saving. It is also important that for a better economic performance there are different conditions that should exist and they are not only related to the recovery but also on guaranteeing the sustainability of economic fluxes. A country to be able to attract new investments needs to have a stable and strong political economy which on the other hand has been recognized as a target closely related to DRM.

A clear reduction of mortality due to natural phenomena is needed and the fact that in most of the industrialized countries the casualties' figures are far lower than those observed in the developing countries, even if facing similar seismic hazard levels, is a good prove and motivation that the targets can be achieved. Development needs to be understood in a way that not only the economic dimension is the one considered for assessment and monitoring purposes but also in terms of actions that are translated into safe, decent and appropriate access for household for all members of a society.

Financial protection against natural events is needed at all governmental scales and the use of CAT-models can clearly provide the order of magnitude for the required resources and for an appropriate risk layering process. The last allows the identification, definition and combination of different options and instruments, either using traditional insurance and reinsurance schemes or alternative risk transfer instruments.

The proposed methodology is well aligned with the SFDRR accounting not only for an improved understanding of disaster risk in different dimensions than the traditional covered through the CAT-models and also by adding accountability for disaster risk management.

7.3 Conclusions on the acceptable risk in earthquake engineering

The acceptable risk concept needs to be incorporated in a direct, explicit and clear way into the earthquake engineering field by means of the earthquake resistant building codes and in the way in which some of the requirements related to seismic safety are included in them. Building codes must address explicitly the objective of life protection and a zero indoor mortality target should be included. Political will to invest, enforce and regularly update building code requirements are fundamental in order to increase resilience and guarantee a sustainable development in earthquake prone areas.

It cannot be acceptable under any circumstance large numbers of people dying as a consequence of the occurrence of earthquakes given that there is, as of today, a good understanding of their occurrence chance, characteristics and potential damages. These last provide information that is useful for specific measures to be taken with the objective of preventing large losses in the human capital besides the protection of property, wealth and heritage which are more related to the stock capital.

Even if a formal definition of an acceptable risk level has not been yet reached, it is important to agree that the current risk level is unsustainable even if disagreeing on how much risk is acceptable.

7.4 Conclusions on the human vulnerability functions

The development of vulnerability functions that account for the human loss dimension in earthquake engineering has been in the recent past a field of continuous research and several advances. Anyhow, it highly depends on the availability of empirical data which are usually available from earthquake damage and consequences databases, the main source for the estimation of lethality ratios.

Because most of the state-of-the-art PSHA are developed in terms of instrumental intensities (i.e. spectral accelerations, velocities and/or displacements) human vulnerability functions should be developed in terms of the same seismic hazard intensity instead of macroseismic ones as it is the case for most of the available ones to date.

Given that there is a close relationship between the structural behaviour and the expected number of casualties from the structural engineering perspective, it is important, in order to guarantee consistency among the risk analyses, to relate the physical vulnerability functions with those used for the estimation of losses considering the human dimension. In this thesis, this has been achieved by developing the human vulnerability functions from the physical ones allowing a common background for all of them and letting them share scopes and limitations.

The fact that significant differences have occurred in terms of deaths and injured in buildings with similar characteristics, subjected to similar seismic demands but located in different countries, is the main difficulty but, at the same, time the biggest challenge for the persistence on the development of human vulnerability functions.

7.5 Conclusions on the mínimum public investment required for seismic safety

The estimation of the order of magnitude of what the minimum public investment on seismic safety should be at societal level with the aim of reducing mortality because of earthquakes, allow establishing a technical allocation of resources. With this in mind, and remembering that these resources are to be used in corrective measures, it can be said that, together with a decrease in the mortality, there can be also a progressive decrease in the amount of the required resources to pursue the overall objective over the time. This allows concluding that the investment on corrective actions related to seismic safety is a finite process which can be incorporated into a public policy in terms of a panorama. The main target of the public policy is to achieve zero mortality because structural collapse due to earthquakes within a time window.

The fact that the public investment on seismic safety can be established by means of a technical approach, also contributes to the accountability and good practices on governance related to DRR. This makes the planned investments applicable over the medium and long-term which, at the same time, can be continuously monitored and updated; the chances of a political management of disasters is thus what in most cases, has left the idea of opportunism.

7.6 Conclusions on the results of the case studies

Conclusions about the results of the different case studies conducted at three different resolution levels are presented. It is important to highlight that, in all the cases, the same probabilistic risk assessment methodology has been used with differences in the input data. This has allowed obtaining the results in terms of the same risk metrics, bearing in mind that not necessarily the results for different resolution levels are directly comparable.

7.6.1 At country level

From the country level case studies developed for 30 countries in LAC and Europe, it can be concluded that there are several countries in which still important investment on corrective measures regarding seismic safety are required in order to reduce earthquake mortality, both in absolute and relative terms. This can be mainly observed where most of the urban centres are located within seismic hazard prone areas (such as in Colombia, Peru and Ecuador) as well as where, due to the geographical extent, it is not possible to have a diversification of the exposure (Trinidad and Tobago, Dominican Republic and Haiti).

From these results, it is also possible to see that in countries with important seismic hazard levels and where important and damaging earthquakes have occurred in the past but, also, where state-of-the-art building codes exist and are complemented with an important enforcement process, such as in Chile and Mexico, lower relative public investment levels are required; it also can be said that they are closer to the zero mortality target.

Regarding the results for Spain and other countries with low seismic hazard levels, such as Belize, Paraguay and Saint Lucia, important care is needed in the way the results are interpreted since the PSHA developed in this thesis considers only instrumental seismicity. The proposed methodology seems to work better in areas where intermediate and high seismic hazard levels exist.

7.6.2 At subnational level

From the subnational case study developed for Colombia, it can be concluded that the methodology can be applied where the required data are disaggregated at subnational administrative units. In the case of Colombia, important differences in the GDP per capita exist which are translated into higher values of what the proposed minimum public investment on seismic safety should be. Results for departments such as Meta, Arauca and Casanare, where important oil exploitation and industries exist, if converted into actions regarding seismic safety of public facilities such as schools and medical centres, can be also translated into tangible improvements of the societal conditions as a consequence of better and higher access of the inhabitants to those services.

There are also the cases of departments where, despite not having the highest seismic hazard levels, due to the population concentration because of the existence of important urban centres (such as Bogotá D.C., Medellín, Cali and Cúcuta), the highest absolute results are found in there.

7.6.3 At urban level

From the urban study of Medellín, Colombia, it can be concluded that, when detailed information regarding exposure and hazard, mainly in terms of seismic microzonations that account for the dynamic soil response by means of spectral transfer functions, important information of high relevance for the decision-making process is obtained. It is of relevance conducting the probabilistic seismic risk assessments that account for both the human and capital stock dimensions at urban level, in order to identify how much, in terms of monetary resources, is needed at local level, since, in the case of Colombia, the management of public facilities and infrastructure is in the hands of the city councils.

In all three cases, it is important, once again, that the same probabilistic risk assessment methodology has been used and that only punctual differences in terms of how the input data were included in the analyses existed.

7.7 Conclusions on the comparison of observed and modelled losses and casualties

The few available cases of comparison of observed damages with modelled ones, are well detailed and have been used for careful post-earthquake surveys. Thus, the review of the validity of CAT-models as well as their improvements, were possible. The availability to perform such comparisons leaves space for the temptation of attempting a calibration process. Nevertheless, a single event cannot be considered as statistically significant and, although providing several opportunities for a better understanding and punctual improvements in the CAT-models, it is not sufficient for that purpose. Doing so, would be equivalent to the development of a ground motion prediction equation with a single strong ground motion record what, in the light of earthquake engineering, is completely unacceptable.

In this, a comparison between the observed and simulated damage in Lorca for an earthquake with characteristics similar to that occurred on May 2011 has been performed. The calculated damage levels have the same order of magnitude, showing that probabilistic approaches, such as the selected one, are useful for the risk quantification process, even if they do not match exactly the actual observed values. The same observation can be made about the estimation of indoor mortality associated to building collapse under the assumption that a very low occupation rate of the residential dwellings existed, mostly because of the time of the event and of the occurrence of a foreshock hours before. An estimation of the direct losses in monetary terms has been also made for the case of the Lorca earthquake, where a gross value of the insured losses is also available. Nevertheless, these figures are not intended to match since the latter consider only the insured buildings and only take into account the insured amount, leaving out the value corresponding to the layers associated to deductibles and insured limits.

In terms of the exposure database used in this case study, many parameters could be captured without an individual survey and, therefore, a grouping process among building classes was followed. Data gathering processes should be encouraged at different resolution levels so that the collected and organized information can be used to refine and improve the damage and loss estimations.

From the observed damage point of view, there are several challenges regarding how damage levels are recorded and classified if a loss evaluation calibration process is performed. Usually qualitative damage scales are used and, therefore, no formal ways to translate those observed damage into loss exist. It is also difficult to capture the damage cost since, usually, after a large event strikes a city, price increases driven by inflation and scarcity of materials occur which are not easy to be distinguished and included in risk assessment.

Finally, it is worth mentioning that after a disaster event there are decisions made not necessarily following technical reasons but economic and urban planning ones. Disaster events may trigger economic boost initiatives, generate new open public space areas and/or stock replacement (even more when resources are available through insurance). Those actions are not predictable since they depend in each case on the economic and political circumstances of the place where the earthquake takes place.

7.8 Future research

Some future research lines related to the different topics covered and explored within this thesis are presented now. They have been identified with the idea of allowing future improvements and completions of the proposed methodology and the expansion of it for the consideration of other natural hazards different than earthquakes.

7.8.1 Human occupancy rates

Being the human occupancy a dynamic exposure characteristic, further research for the estimation of this parameter within the exposure databases for different times of the day, different days of the week and even considering seasonality issues is required. So far, studies for specific cities, mostly in the USA, are available and have been used in other places of the world since no more data are available. Anyhow, cases as the Gorkha Earthquake in April 2015 have shown that their use is not completely appropriate and that, at least, regional variations should be studied.

7.8.2 Regional lethality ratios

Establishing the lethality ratios associated to the building classes accounting for geographical variations is recommendable. From the available earthquake damage and consequences databases, clear and important differences can be observed among building belonging to the same class that have been subjected to earthquakes with similar characteristics. Factors related to the roof characteristics can be reasons for the definition of specific and regional lethality ratios and, together with the medical field, is a research line that can contribute to the development of better human vulnerability functions. These are useful not only for the risk assessments, such as the ones included in this thesis, but also for the development of comprehensive emergency plans at urban level.

7.8.3 Integration of *YLL* into the holistic seismic risk assessment framework

Considering the importance that losses in the human capital have within a society, the possibility of a robust quantification of such losses opens the chance for an integration of these results within holistic risk assessment frameworks, specifically that for the estimation of the *USRi*. In different case studies, the estimation of overall rates for deaths and injured, in terms of average annual values or overall ones associated to the occurrence of a particular event, has been considered within the physical risk index. Anyhow, the possibility to include values that go beyond the estimation of the figures and highlight the relevance of losses in the human capital dimension can create the chance to further expand the scope of the holistic risk assessment approaches. This would bring higher benefits to the places where they are applied and also to provide consistent, robust and valuable information to decision-makers and stakeholders involved in the DRM and DRR processes.

7.8.4 Estimation of injury types because of earthquakes

Even if with todays' data it is possible to develop human vulnerability functions in terms of injured, a detailed classification of the injury types is not yet available and, therefore, a reliable estimation of *YLD* in a probabilistic and prospective manner is not yet possible. Injury types will depend on the characteristics of the building classes and, as in the case of deaths, important variations are expected to appear within the earthquake damage and consequences databases as a function of the geographical location. By being able to estimate these distributions, it would be also possible to estimate, in a prospective way, the *DALY* for earthquakes which can open the discussion on what should be the minimum public investment on seismic safety not only related to mortality but also to injuries, considering medical expenses and the implications on social expenditure.

7.8.5 Consideration of other hazards different than earthquakes

The proposed methodology for the quantification of the average annual lost production due to premature mortality can be applied to any natural or man-made hazard whose representation can be obtained in terms of either stochastic sets or intensity exceedance curves and also for which the development of human vulnerability functions is possible. For the last, some research already exists for natural hazards such as of tsunami, floods and cyclonic winds.

By being the average annual lost production due to mortality a metric based on the *AAL*, the estimation of the value associated to different hazards can be performed in a direct way, so that the results of independent risk assessments can be grouped and still constitute a valid and robust multi-hazard approach. This can provide valuable information about locations where other hazards have the same and even higher relevance than earthquakes.

Annex 1

PROBABILISTIC SEISMIC HAZARD ANALYSES AT GLOBAL AND LOCAL LEVEL

This annex presents the details of three different PSHA developed at different resolution scales whose results, in terms of sets of stochastic events, were used for the probabilistic physical and human risk assessments for Latin America, the Caribbean, Colombia and Spain. In all the cases the same probabilistic methodology and framework has been used even if there exist particular differences in terms of input data and geometric models as will be shown next.

The selected PSHA methodology allows accounting in a comprehensive way for the different uncertainties in the calculation process such as the ones associated to the definition of the seismogenetic sources, their geometry, the estimation of the seismicity parameters and the attenuation patterns of the seismic waves.

When seismic hazard is assessed by probabilistic means, results are usually expressed in terms of the intensity exceedance rates for any site of interest, from where the exceedance probability of certain intensity value during a timeframe can be derived (e.g. 7% exceedance probability in 75 years). Although both results are presenting the same information, it is worth to highlight that when results are expressed in terms of exceedance rates, the definition of an arbitrarily selected timeframe to contextualize the results is not needed. The hazard intensity values and the units for which the PSHA is performed depend on the selection of the GMPEs as well as with the spectral ordinate range that they cover.

Once the seismicity and attenuation patterns of all seismogenetic sources is known, seismic hazard can be calculated considering the sum of the effects of the totality of them and the distance between each seismogenetic source and the point of interest. Seismic hazard, expressed in terms of the intensity exceedance rate, $\nu(a)$, is calculated as follows (Ordaz, 2000):

$$\nu(a)=\sum_{n=1}^{N}\int_{Mo}^{Mu}-\frac{\partial\lambda}{\partial M}\Pr(A>a\,|\,M,R_i)dM \qquad \text{(A1.1)}$$

where the sum covers all N seismogenetic sources, $Pr(A>a/M,\ R_i)$ is the probability that the intensity exceeds certain value given the magnitude M and the distance between the source and the site of interest R_i of the event. $\lambda_i(M)$ functions are the activity rates of the seismogenetic sources. The integral is performed from the threshold magnitude M_0, to the maximum magnitude M_u, which indicates that for each seismogenetic source, the contribution of all magnitudes is accounted for.

It is worth noting that the previous equation would be exact if the seismogenetic sources were points. In reality, they are treated as volumes and because of that, epicentres do not occur within the centre of the sources but, with equal spatial probability, within any point of the corresponding volume. This is considered in the geometrical model of the area by subdividing the sources into simpler geometries (triangles), on which the gravity centre is assumed to concentrate the seismicity of each triangle as shown in Figure A1-1. The subdivision is performed recursively until reaching a small enough triangle size to guarantee the precision in the integration of Equation A1.1.

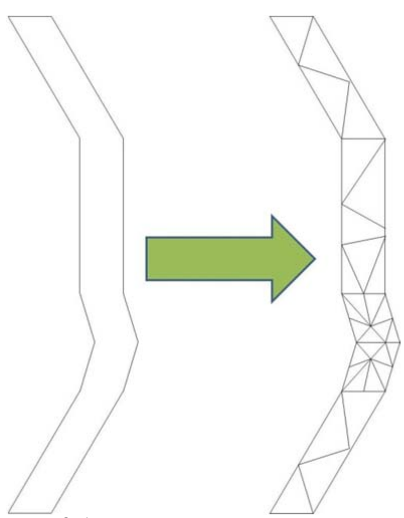


Figure A1-1 Subdivision of the seismogenetic sources into simpler geometries

Since it is assumed that once magnitudes and distances are known the intensity follows a lognormal distribution, the probability $Pr(A>a/M,\ R_i)$ is calculated using the following expression (Ordaz, 2000):

$$\Pr(A>a\,|\,M,R_i)=\Phi\left(\frac{1}{\sigma_{Lna}}\ln\frac{\text{MED}(A\,|\,M,R_i)}{a}\right) \qquad \text{(A1.2)}$$

where Φ(·) is the normal standard distribution, MED(A|M, Ri) is the median of the intensity, given by the associated GMPE for known magnitude and distance, and σLna accounts for the standard deviation of the natural logarithm of the intensity. It is worth noting that the median is not the same that the mean value, even if they are the same on a logarithmic scale9.

Although there are different approaches to calculate seismic hazard using Markov, Semi-Markov and renovation models (Kiremidjian and Agnanos, 1988), for PHSA it is common practice to assume that seismic activity follows a Poissonian process, reason for which the probability of exceeding, at least once, the intensity parameter a within a timeframe t can be related to the annual occurrence frequency, generally denoted as λ. According to this, the probability that there is an exceedance (of the intensity parameter a) within an arbitrarily selected timeframe t can be calculated as follows:

$$\Pr(1 \text{ exceedance in } t \text{ years}) = 1 - e^{-\lambda t} \qquad \text{(A1.3)}$$

Now, assuming that the exponent in Equation A1.3 is small enough, the equation can be simplified into:

$$\Pr(1 \text{ exceedance in 1 year}) = \lambda t = \lambda \qquad \text{(A1.4)}$$

With this, the Poisson seismicity models basically have the following characteristics:

- The sequence of the events does not have memory and the future occurrence of one event does not have anything to do with the fact that a previous one occurred.
- Events occur randomly over the time, space and magnitude domains.
- To use this approach in PSHA, it is required to remove the after and foreshocks in the earthquake catalogue used to estimate the seismicity parameters of the seismogenetic sources.
- The relationship is truncated to a threshold magnitude and a maximum magnitude (M_0 and M_U) for practical purposes. The last has also associated certain degree of uncertainty.

For these analyses, a local seismicity Poisson model has been selected where the activity of the i^{th} seismogenetic source is specified by means of the magnitude exceedance rate $\lambda_i(M)$, generated by it, which is a continuous distribution of the events. That magnitude exceedance rate relates how frequently earthquakes with magnitude higher than a selected value occur. The

[9] Since seismic intensities are quantified in terms of absolute values, what is calculated is the median and not the mean.

$\lambda_i(M)$ function is a modified version of the Gutenberg-Richter relationship (1954) and then, seismicity is described in the following equation using a procedure like the one proposed by Esteva (1967) and Cornell and Van Marke (1969):

$$\lambda(M) = \lambda_0 \frac{e^{-\beta M} - e^{-\beta M_u}}{e^{-\beta M_0} - e^{-\beta M_u}} \tag{A1.5}$$

where M_0 is the selected threshold magnitude and λ_0, β_i, y M_U are the seismicity parameters that define the magnitude exceedance rate for each seismogenetic source. Those parameters are unique for each source and can be estimated by means of statistical procedures for the first two. For M_U, specialized studies combined with expert criteria and historical data are usually employed, although recent works have found that little information can be found about this parameter from earthquake history (Zöller and Holschneider, 2016).

Because seismic activity is assumed to follow a Poissonian process, the probability density function for the magnitudes is as follows:

$$p(M) = -\frac{d\lambda(M)}{dM} = \lambda_0 \beta \frac{e^{-\beta M}}{e^{-\beta M_0} - e^{-\beta M_U}}, M_0 \le M \le M_U \tag{A1.6}$$

it is evident that each seismogenetic source activity is characterized by a set of parameters based on the available information. Those parameters are:

- Earthquakes recurrence rate for magnitudes higher than the selected threshold (M_0): corresponds to the average number of events by year with magnitude higher than the threshold magnitude occurring in a given source.
- β value: represents the slope of the initial part of the logarithmic regression of the magnitude recurrence plot. It accounts for the ratio between large to small events in each source.
- Maximum magnitude (M_U): represents the maximum magnitude of plausible events to occur within the considered source.

Figure A1-2 shows the hypothetical magnitude exceedance rates plots for two seismogenetic sources where the red line is associated with a source with higher seismic activity and higher potential of generating events with large magnitudes if compared with the blue line. For this example, both sources have a M_0 equal to 3.5 but, meanwhile λ_0 is equal to 1.0 in the source represented through the continuous line, it is equal to approximately to 30 in the dotted one.

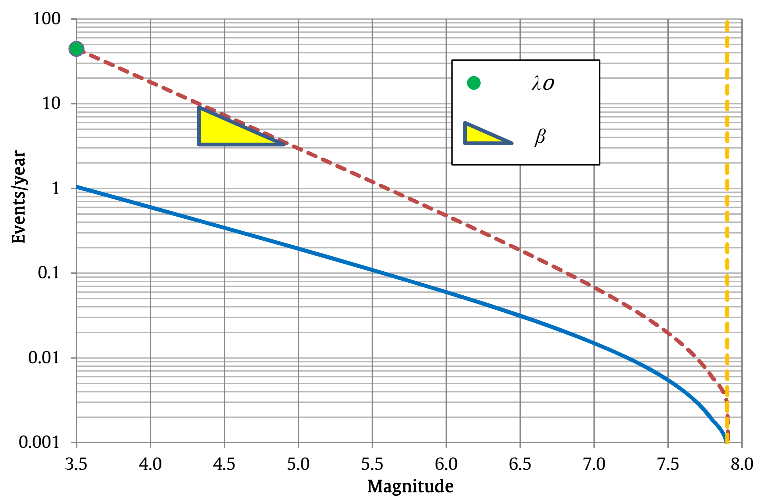


Figure A1-2 Example of magnitude exceedance rate plots

Once all the historical events in the earthquake catalogue have been assigned to the seismogenetic sources, the calculation of the seismicity parameters λ_o and β_i was performed using the maximum likelihood method (Bender, 1983; McGuire, 2004).

λ_o parameter, which is a rate, is calculated as the number of events N associated to each seismogenetic source observed over the timeframe t

$$\lambda_0 = \frac{N}{t} \tag{A1.7}$$

That highlights the importance to determine the completeness window which can be done by for example, following the procedure proposed by Tinti and Mulargia (1985).

On the other hand, β_i parameters are calculated by means of

$$\beta = \frac{N}{\sum_{i=1}^{N} M_i - M_0} \tag{A1.8}$$

where, again, N is the number of events associated to the source, M_i is the magnitude of each event and M_0 is the threshold magnitude of each source. Because β_i parameters are considered as a random variable that represent a function that is not completely defined and understood, it is important to also calculate its coefficient of variation, $CV(\beta)$ by dividing its mean value between the standard deviation. After simplifying terms, it can be reduced to the following equation:

$$CV(\beta) = \frac{1}{\sqrt{N-1}} \tag{A1.9}$$

Finally, it is necessary to determine the M_U associated to each seismogenetic source. Because there is uncertainty in this parameter, it is usually not considered as a fixed value but as a random variable which follows a truncated normal distribution, computed from its expected value and its standard deviation, truncated as shown in Figure A1-3.

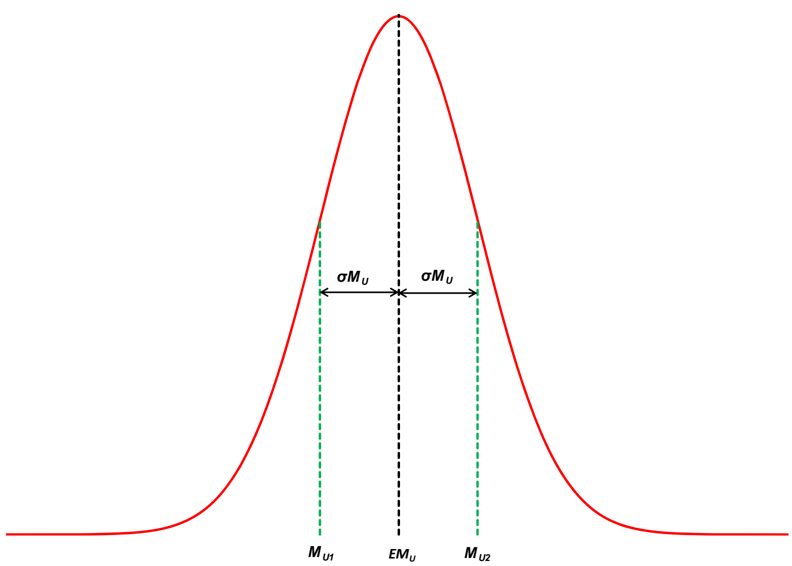


Figure A1-3 Normal distribution for the estimation of the maximum magnitude

A1.1 Probabilistic seismic hazard analysis at global level

Within the framework of the Global Assessment Report on Disaster Risk reduction 2015 – GAR15 (UNISDR, 2015a) a global, consistent and fully probabilistic PSHA was developed at global level by CIMNE and Ingeniar (2015) as an update of the previous work of Ordaz et al. (2014). Seismic hazard is estimated at bedrock level based on instrumental seismicity compiled using different international sources.

Because of the geographical scope of this analysis and acknowledging that there is a high difficulty in reducing the epistemic and random uncertainties at this scale, a series of assumptions and simplifications were made in order to handle data in a similar way on every corner of the globe. For this reason, a smoothed seismicity approach was selected to estimate the seismicity parameters and a coarse grain regionalization of the globe into seismo-tectonic provinces with different characteristics was made.

Using the 50 regions defined by Flinn and Engdahl (1965), shown in Figure A1-4, 401 seismo-tectonic provinces were defined (see Figure A1-5) after considering depths and focal mechanisms from historical earthquakes. For each of the seismo-tectonic provinces a GMPE and a M_U were also assigned as shown in Figure A1-6 for the Latin America and the Caribbean region.

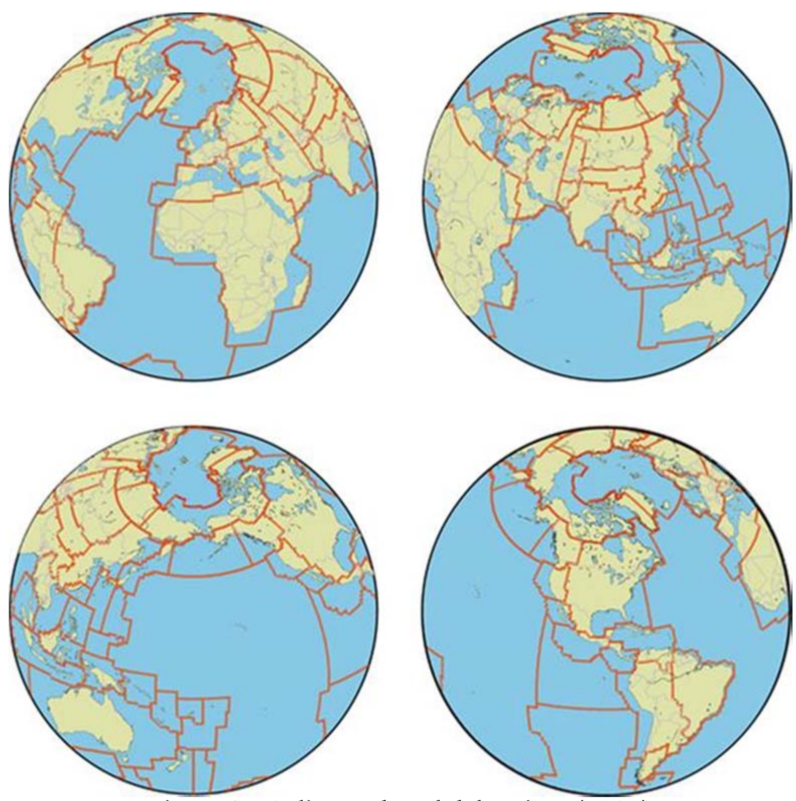


Figure A1-4 Flinn and Enghdal regions (1965)

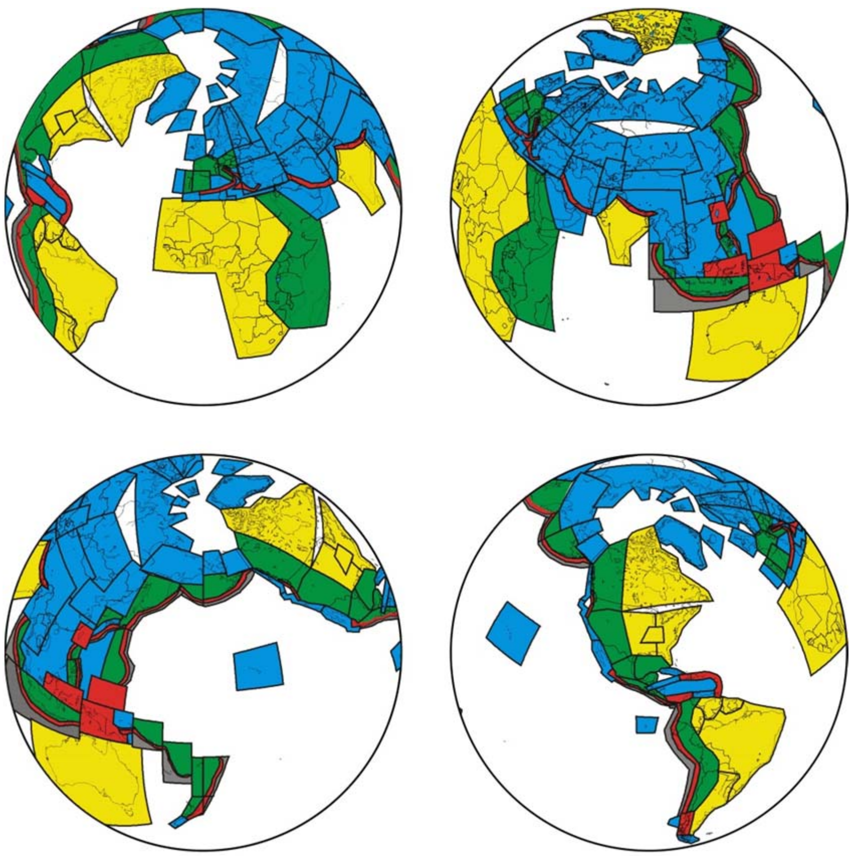


Figure A1-5 Seismo-tectonic provinces used in the PSHA

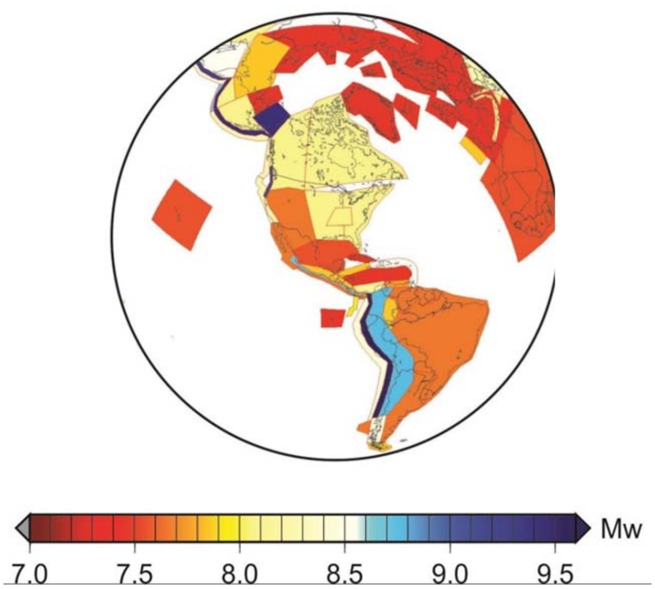


Figure A1-6 Assigned M_U for the seismo-tectonic provinces in Latin America and the Caribbean

A total of 162,516 earthquakes are included in the final catalogue which for the selected M_0 (4.5) is considered as complete from 1973 onwards. For calculating the parameters of seismic activity, the method of smoothed seismicity proposed by Woo (1996) was used. For this procedure, 0.3 degrees spaced grids were selected and with this, the whole globe was covered. The following smoothing parameters were selected:

- R_{min}=0.3 degrees
- R_{max}=1.2 degrees

A weighting process is also required for the definition of these values as a function of the focal distances of the events to the node on the grid that is being characterized. The weights for the smoothing process are calculated as follows:

- C/R_{min} if $R<R_{min}$
- C/R if $R_{min}<R<R_{max}$
- 0 if $R>R_{max}$

Where R is the distance between the seismic focal point (information registered in the catalogue) and the node for that the smoothed seismic activity is calculated.

Due to the variation in the depth of the earthquakes, identified from the catalogue, the classification of three different ranges of depth was undertaken being them 0-30 km 30-60 km and 60+ km. A depth of 15, 45 and 75 km is assigned respectively to each one of these grids when calculating the seismic hazard.

The values of the parameter β are truncated between 1.8 and 3.0 for any node in the grid. Figure A1-7 shows the distribution of the $\lambda_0$for the 60+km depth range and Figure A1-8 shows the distribution of the β parameter for the 30-60km depth range.

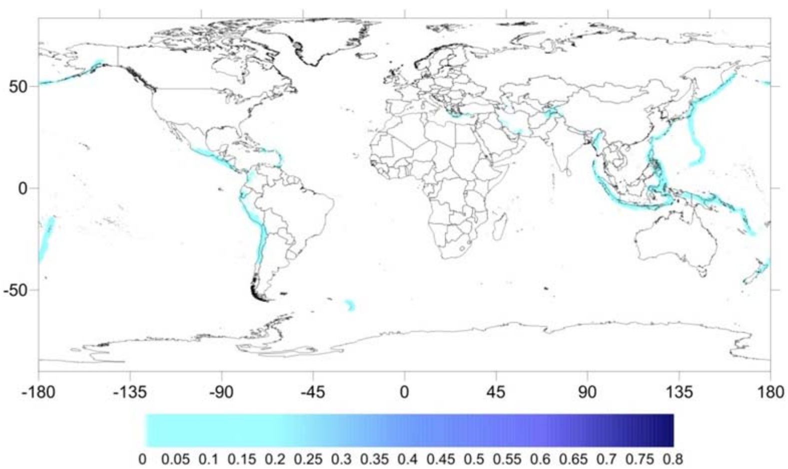


Figure A1-7 $\lambda_0$grid for the 60+km depth range

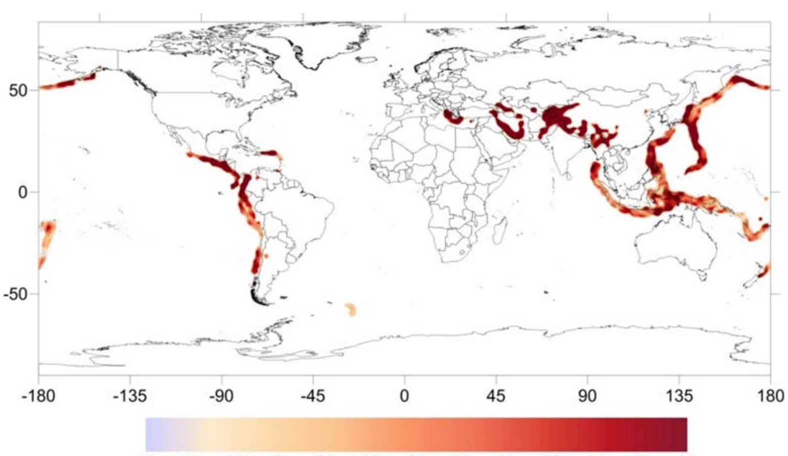


Figure A1-8 β grid for the 30-60km depth range

A unique GMPE has been assigned to each seismo-tectonic province according to their characteristics:

- Zhao et al. (2006) – interface for interplate subduction thrust
- Zhao et al. (2006) – intraslab for intraslab subducting plate
- Atkinson and Boore (2006) for stable continental
- Cauzzi and Faccioli (2008) for active crustal and off shore
- Chiou and Youngs (2008) for strike slip

In the GMPEs' parameters definition, a Vs_{30} value of 1,100 m/s was explicitly included, to guarantee the consistency of the analysis along the globe. All of them cover a wide range of spectral ordinates allowing that the hazard intensities in the stochastic event set allow assessing risk for buildings of different characteristics.

Based on the parameters of seismic activity (λ_0 and β-values) calculated for each node, stochastic events are generated in each of them for different magnitudes and occurrence frequencies; this latest parameter accounts for the time variability of occurrence. It is evident that in this analysis with the smoothed seismicity approach, each node is treated as a source.

From the stochastic event set (*.AME file) with more than 1 million events and after integrating hazard in a probabilistic manner, seismic hazard maps were calculated for several fundamental periods and mean return periods. Figures A1-9 and A1-10 show some of those maps for PGA and 0.2s and for 475 and 2,475 years mean return period respectively.

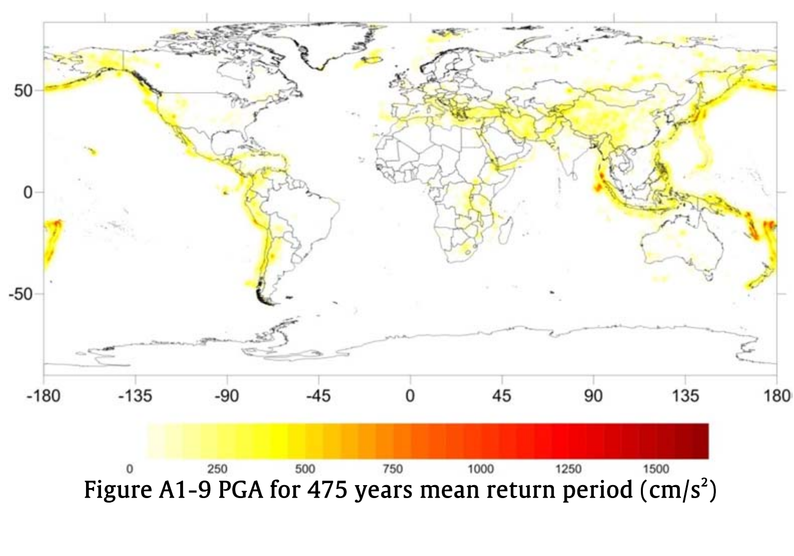


Figure A1-9 PGA for 475 years mean return period (cm/s^2)

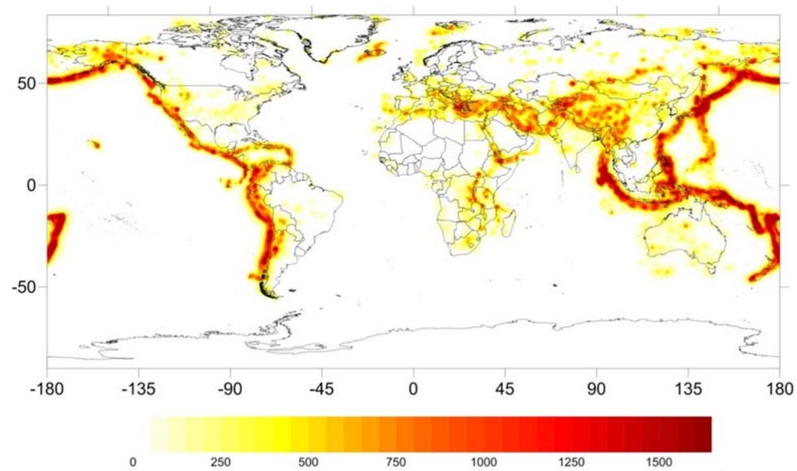


Figure A1-10 0.2s for 2,475 years mean return period (cm/s^2)

A1.2 Probabilistic seismic hazard analysis for Colombia

A recent update of the Colombian earthquake resistant building code for bridges (CCP-14) was developed by the Colombian Association for Earthquake Engineering (AIS). Among the different tasks developed, the values for the seismic design coefficients, compatible with the functional form of the selected elastic design spectra were established. For that reason an update of the probabilistic seismic hazard assessment was performed from which the seismic design coefficients have been estimated for Colombia. With respect to the latest national seismic hazard assessment, 5 more years of earthquake records and the consequent better understanding of the Colombian seismic environment are included in the analysis by updating the seismicity parameters of the seismogenetic sources and using GMPEs calibrated with local strong ground motion records. The stochastic event set generated from this PSHA was used for the estimation of average annual deaths, number of life-lost years and lost economic productivity presented in Chapter 5 of this thesis at subnational level for Colombia. Next, a summary of the PSHA is described.

This PSHA uses the tectonic model previously used in other seismic hazard assessments in Colombia (AIS, 2010; Salgado-Gálvez et al., 2010) but with changes in the seismicity parameters as well as in the GMPEs, both justified by the collection of 5 additional years of local strong ground motion records.

Following the approach proposed by Esteva (1970) the Colombian territory is divided into different tectonic zones represented by means of seismogenetic sources and for each of them, a series of seismicity parameters that account for the occurrence process of earthquakes are calculated. A GMPE is assigned to each source to finally establish the annual exceedance rates for different intensity measures, in this case spectral accelerations (*Sa*), and also to generate an stochastic event set.

38 seismogenetic sources have been considered and are represented using the area source geometric model where each of them is described by a plane defined by different vertexes that provide information about their location and depth. Seismogenetic sources are classified as shallow and deep in this analysis according to the depth ranges of the seismic activity expected on them. The first category covers seismic activity up to 60km whereas the second category represents the seismic activity with deeper activity. In total, 33 shallow and 5 deep sources are modelled as shown in Figure A1-11.

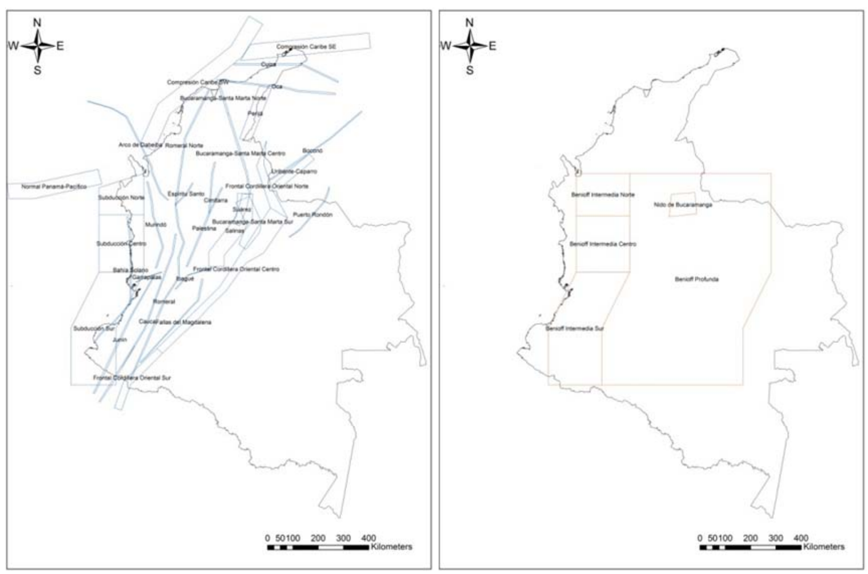


Figure A1-11 Shallow (left) and deep (right) seismogenetic sources for Colombia

The λ_0 and β parameters are estimated using statistical methods based on the instrumental seismicity that, in this case, corresponds to the one used in the national seismic hazard assessment developed in 2010 (AIS, 2010) complemented with information of the NEIC-USGS (NEIC, 2014) and the ISC-GEM (Storchak et al., 2013) up to December 31 2013. M_0 has been set at 4.0 for all seismogenetic sources and the M_U values of the 2010 national seismic hazard study were used. Figure A1-12 shows the values of λ_0 for the considered sources whereas Figure A1-13 shows the values of the β parameter for them.

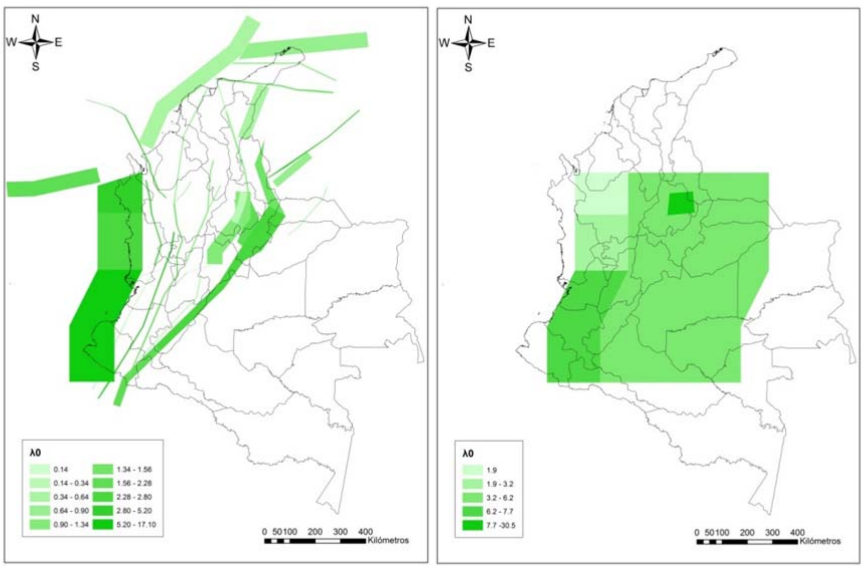


Figure A1-12 λ_0 values for shallow (left) and deep (right) seismogenetic sources

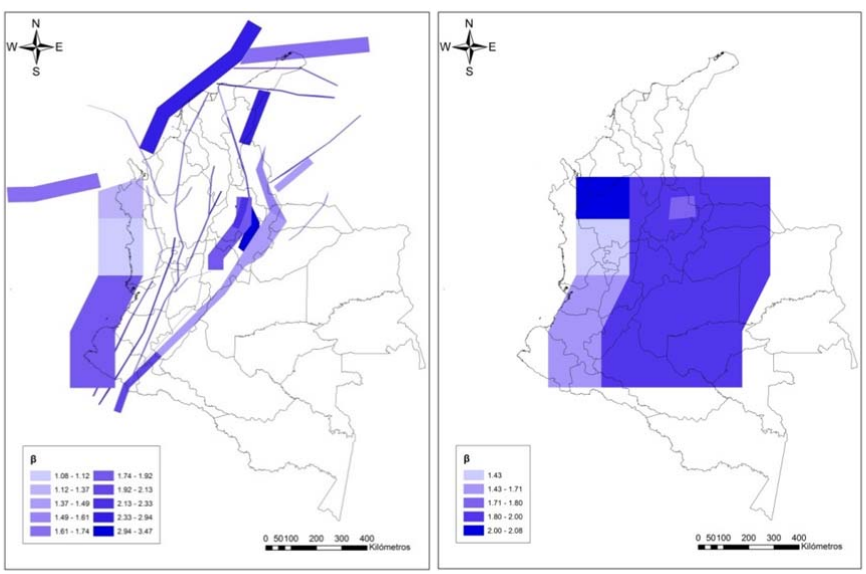


Figure A1-13 β values for shallow (left) and deep (right) seismogenetic sources

The GMPEs used in this case correspond to those developed by Bernal (2014) which use a genetic algorithm procedure for their calibration based on local strong ground motion recordings. This GMPE has been defined for subduction and intraplate activity and a summary for selected magnitudes, in terms of peak ground acceleration (PGA), is shown in Figure A1-14.

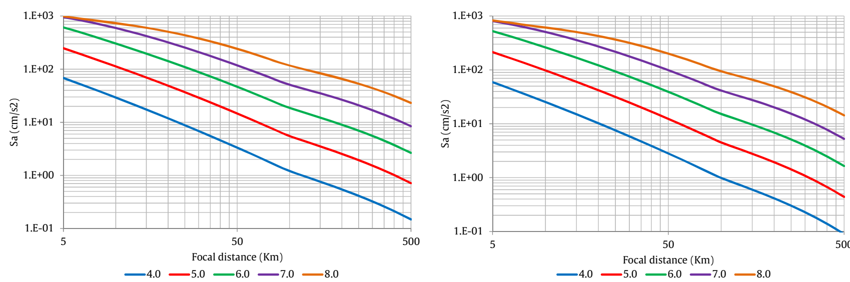


Figure A1-14 Intraplate and subduction GMPEs (PGA). Magnitudes in M_w

Hazard maps for any mean return period and several spectral ordinates can be obtained for Colombia using the stochastic event set. As an example, Figures A1-15 and A1-16 show the seismic hazard results in terms of PGA for 475 years mean return period and 0.3s for 975 years mean return period respectively. From them it is evident that the transition between acceleration levels is much more clearly marked if compared to the optimum design approach presented in Chapter 4.

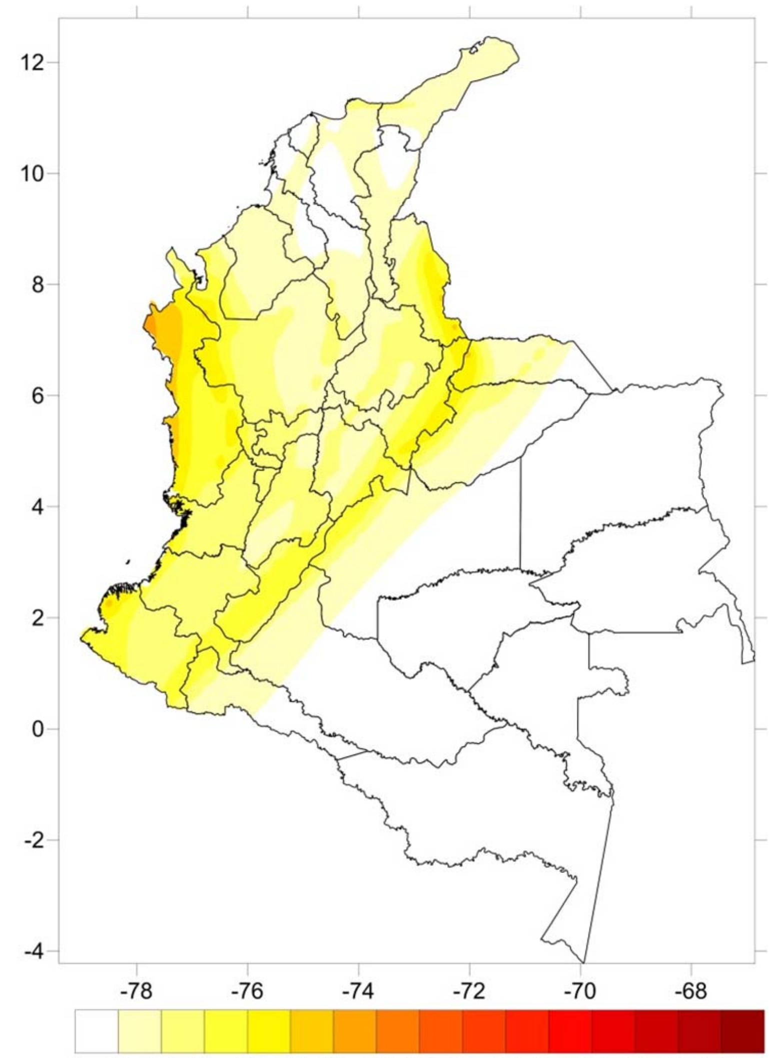


Figure A1-15 PGA for 475 years mean return period (cm/s^2)

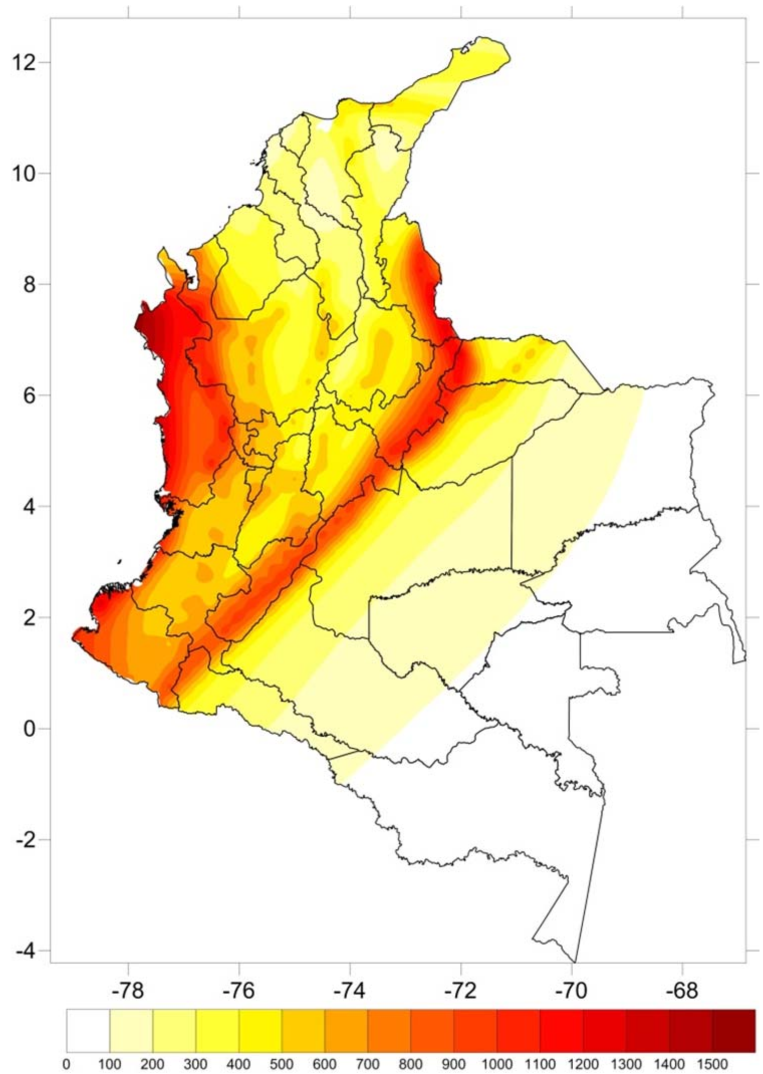


Figure A1-16 0.3s for 975 years mean return period (cm/s^2)

A1.3 Probabilistic seismic hazard analysis for Spain

For the PSHA in Spain, a recompilation of different existing tectonic zonations for the country was done, considering the works of Jiménez and García-Hernández (1999), Grünthal et al. (1999), Jiménez et al. (2001), Buforn et al. (2004), García-Mayordomo (2005), García-Mayordomo et al. (2007), Benito and Gaspar-Escribano (2007), Vilanova and Fonseca (2007) and IGN and UPM (2013). There are numerous similarities in the general procedure followed to define the seismic regions and seismogenetic sources for Spain in recent national and local seismic hazard studies. However, within the framework of the SHARE (Seismic Hazard Harmonization in Europe) project (Woessner et al., 2015) several European specialists defined a set of homogeneous and continuous seismogenetic sources. That last mentioned tectonic zonation corresponds to the one used in this work which can be considered complete and detailed enough for the purpose of the assessment.

A total of 52 seismogenetic sources were considered which are associated to shallow (0-60 km) seismicity as shown in Figure A1-17. For practical purposes, it is assumed that events occurring at depths higher than 60km do not contribute to the seismic hazard levels and do not generate relevant strong ground motion intensities that may cause damages on the exposed buildings and infrastructure.

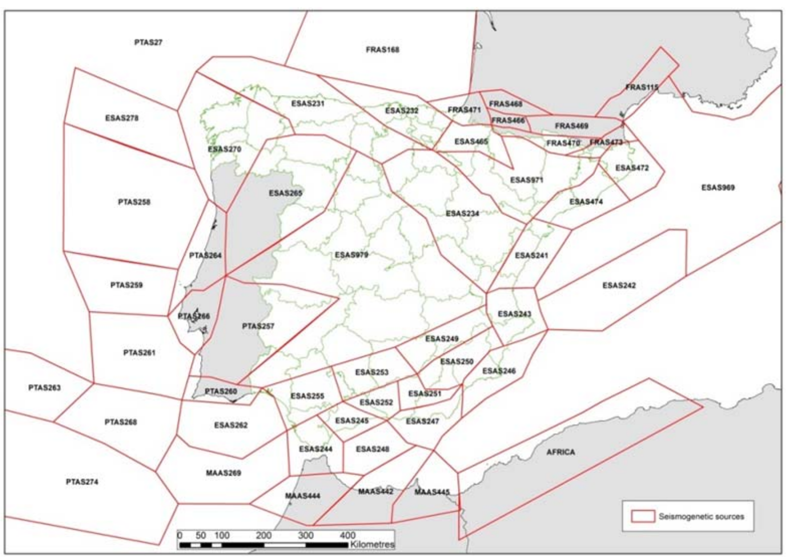


Figure A1-17 Seismogenetic sources for the PSHA in Spain

For this study, the National Geographical Institute - *Instituto Geográfico Nacional* earthquake catalogue (IGN, 2013) was used because for the Spanish context, is the one with higher reliability in terms of both, completeness and quality. Additionally, it was complemented with the instrumental earthquakes catalogue developed by the International Seismological Center in the framework of the Global Earthquake Model initiative (Storchak et al., 2013). The homogenization of the magnitudes to magnitude moment (M_W) was done following the recommendations made by IGN and UPM (2013) for those events whose magnitudes were reported in *Mb* or *Ms*. Initially the catalogue had 87,686 events but after the removal of events with either depth or magnitude parameters not reported and also, the removal of events with magnitudes lower than 3.5 and depths higher than 60 km, 3,643 events remained.

Because a seismicity model that follows a Poisson process has been selected, one of the assumptions and conditions for its use has to do with the independency among the events. For this, a removal of fore and aftershocks was followed using a similar methodology to the one proposed by Gardner and Knopoff (1974). After this process, a total 2,629 events were included in the final catalogue.

Finally, completeness verification for the selected threshold magnitude (M_0) is conducted and according to the procedure proposed by Tinti and Mulargia (1985) it was found that from 1980 on, the catalogue is complete for the selected M_0.

Figure A1-18 shows the λ_0 value for the 52 seismogenetic sources considered in the model for Spain whereas Figure A1-19 shows the β values calculated for each of them.

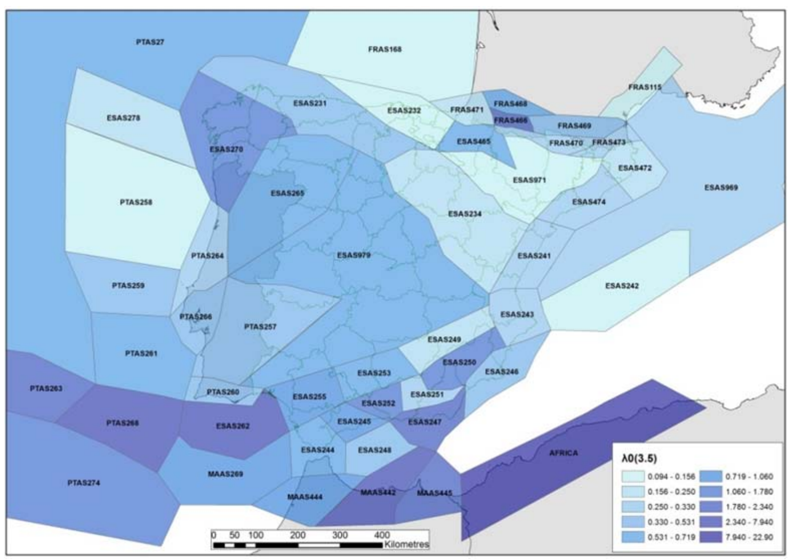


Figure A1-18 λ_0 by source for Spain

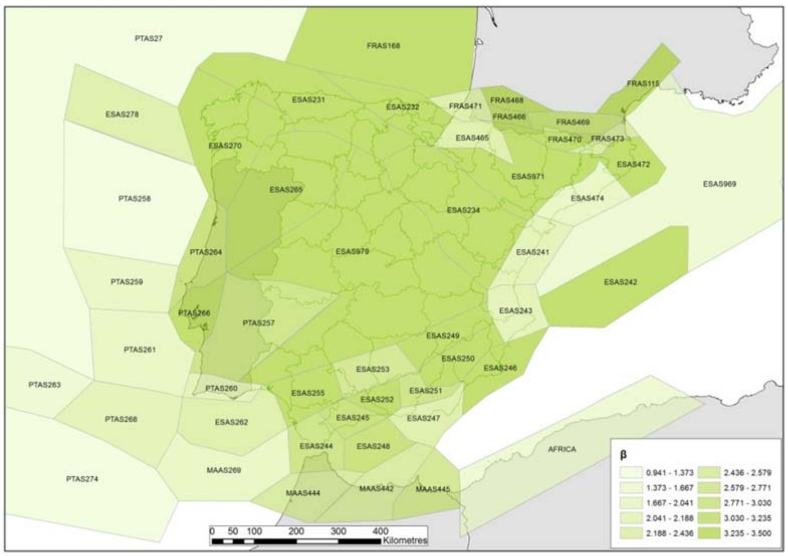


Figure A1-19 β by source for Spain

For this study, the GMPE proposed by Ambraseys et al. (2005) has been selected, that besides accounting for the magnitude and distance as most GMPE, also considers the faulting mechanism and soil conditions. This GMPE has been calibrated with an instrumental earthquake database for Europe and the Middle East using regression analysis that includes a set of weighting factors. This GMPE is defined for spectral ordinates between 0.0 and 2.0s which is sufficient enough for the purposes of the risk assessment developed in this thesis. Figure A1-20 shows the GMPE for PGA and three different magnitudes.

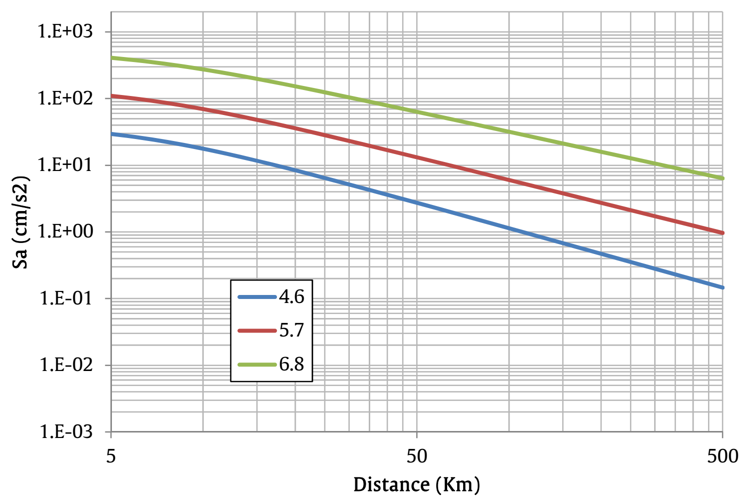


Figure A1-20 Ambraseys et al. (2005) GMPE for PGA and three magnitudes

As in the previous cases, as a result of the probabilistic integration of the contribution of the different sources and magnitudes at different locations within Spain, it is possible to obtain seismic hazard maps as the one shown in Figure A1-21 in terms of PGA and for 475 years mean return period.

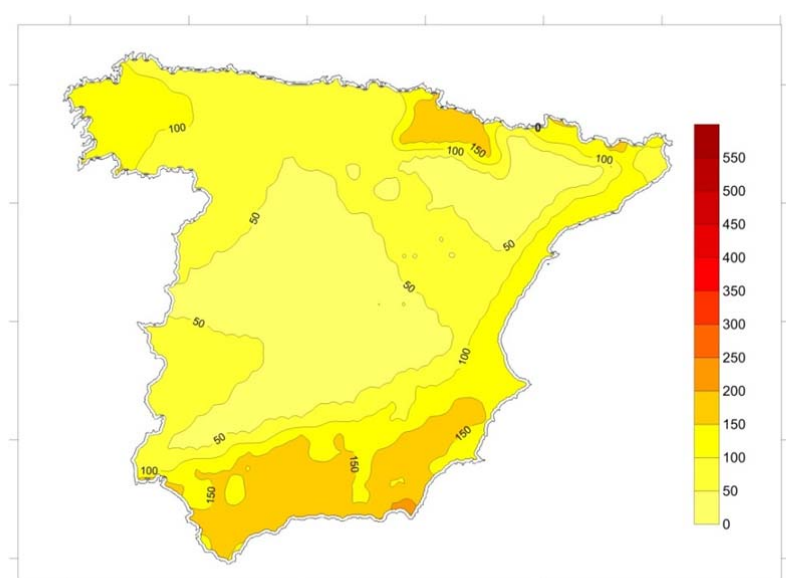


Figure A1-21 PGA for 475 years mean return period (cm/s^2)

After the occurrence of the May 2011 earthquake in Lorca, several discussions arose regarding the validity of previous PSHA in Spain. It is important to bear in mind that for the reasons well explained by Iervolino (2003), it is not correct to compare an event with the integrated hazard levels in terms either of hazard maps for fixed mean return periods, UHS or hazard curves. All of them, when estimated using probabilistic approaches consider the participation of different plausible events with different locations, magnitudes and even associated to different seismogenetic sources and what needs to be verified is if, based on the underlying data of the PSHA, events with the location and characteristics of the real were considered.

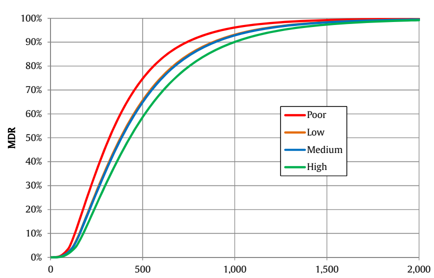
Annex 2

SUMMARY OF THE PHYSICAL AND HUMAN VULNERABILITY FUNCTIONS USED IN THIS THESIS

This annex shows in a graphic way the physical vulnerability functions chosen for the probabilistic risk assessments at different resolution level in this thesis as well as the human vulnerability functions developed using the procedure explained in Chapter 5. For each building class, when applicable, building code categories (i.e. poor, low, medium and high) are shown. The label of each graphic explains the selected *MDR* from where building collapse is assumed to be feasible to occur as well as the assigned lethality ratio. Table A2-1 shows the description of the building class according to the code used in the labels.

Table A2-1 List of typologies and abbreviation codes used for the vulnerability functions

Code	Description
AD1L	Adobe
C1H	Reinforced concrete moment frames (high-rise)
C1L	Reinforced concrete moment frames (low-rise)
C1M	Reinforced concrete moment frames (mid-rise)
C3H	Reinforced concrete frame with unreinforced masonry infill walls (high-rise)
C3L	Reinforced concrete frame with unreinforced masonry infill walls (low-rise)
C3M	Reinforced concrete frame with unreinforced masonry infill walls (mid-rise)
C4H	Reinforced concrete frames with concrete shear walls (high-rise)
C4L	Reinforced concrete frames with concrete shear walls (low-rise)
C4M	Reinforced concrete frames with concrete shear walls (mid-rise)
CM1L	Confined masonry walls
Non-engineered	Non-engineered dwellings
PC1H	Precast concrete tilt-up walls (high-rise)
PC1L	Precast concrete tilt-up walls (low-rise)
PC1M	Precast concrete tilt-up walls (mid-rise)
RM1M	Reinforced masonry bearing walls (mid-rise)
RM2L	Reinforced masonry bearing walls with precast concrete diaphragms (low-rise)
RM2M	Reinforced masonry bearing walls with precast concrete diaphragms (mid-rise)
S1H	Steel moment frame (high-rise)
S1L	Steel moment frame (low-rise)
S1M	Steel moment frame (mid-rise)
S3	Steel light frame
S4M	Steel frame with cast-in-place R/C shear walls (mid-rise)
TA1L	Tapia (earthen dwelling)
URML	Unreinforced masonry bearing walls (low-rise)
URMM	Unreinforced masonry bearing walls (mid-rise)
W1	Wood, light frame



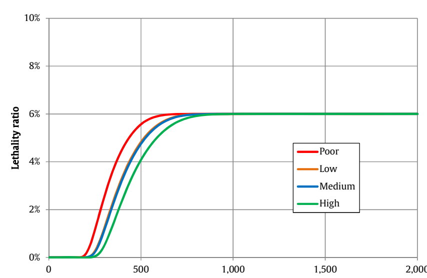


Figure A2-1 Physical (left) and human (right) vulnerability functions for AD1L building class. *MDR*=50%; *LR*=6%

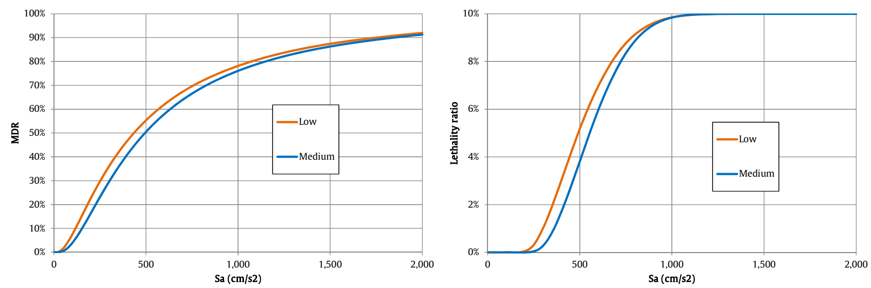


Figure A2-2 Physical (left) and human (right) vulnerability functions for C1H building class. *MDR*=55%; *LR*=10%

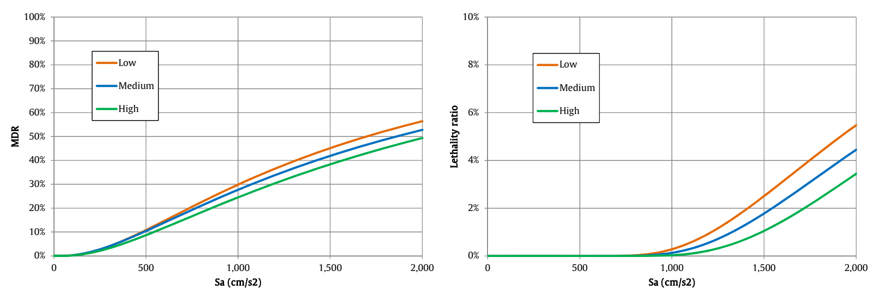


Figure A2-3 Physical (left) and human (right) vulnerability functions for C1L building class. *MDR*=55%; *LR*=10%

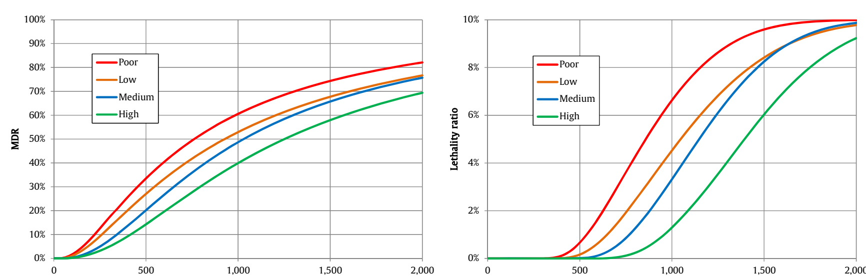


Figure A2-4 Physical (left) and human (right) vulnerability functions for C1M building class. *MDR*=55%; *LR*=10%

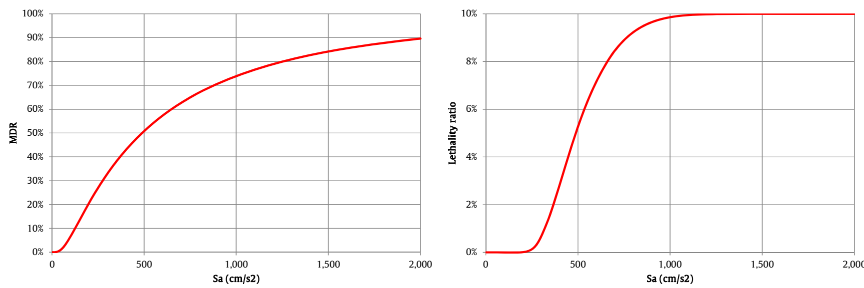


Figure A2-5 Physical (left) and human (right) vulnerability functions for C3H (low code) building class. *MDR*=50%; *LR*=10%

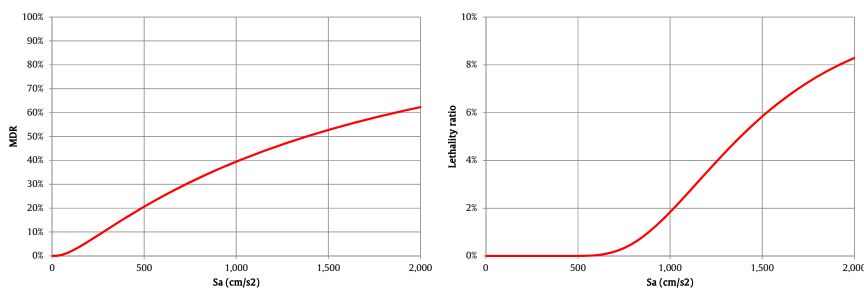


Figure A2-6 Physical (left) and human (right) vulnerability functions for C3L (low code) building class. *MDR*=50%; *LR*=10%

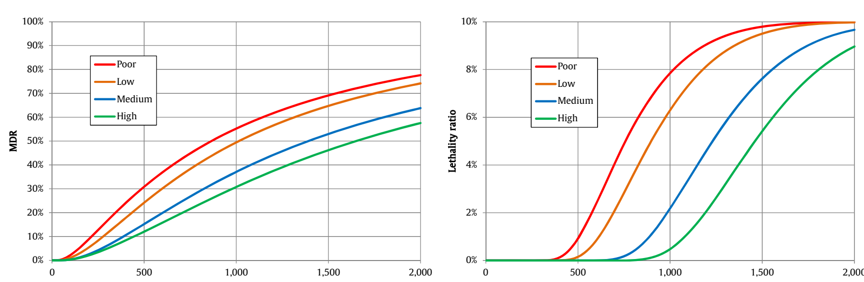


Figure A2-7 Physical (left) and human (right) vulnerability functions for C3M building class. *MDR*=45%; *LR*=10%

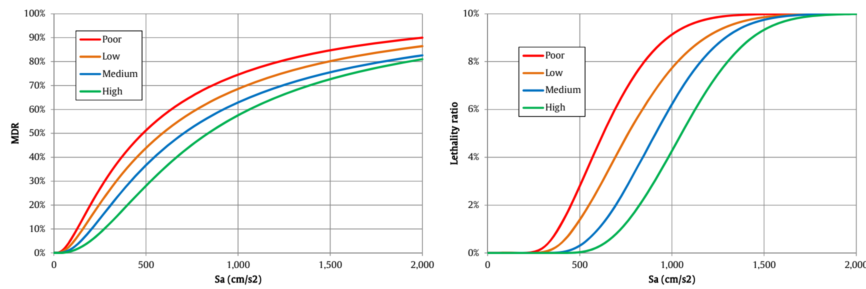


Figure A2-8 Physical (left) and human (right) vulnerability functions for C4H building class. *MDR*=60%; *LR*=10%

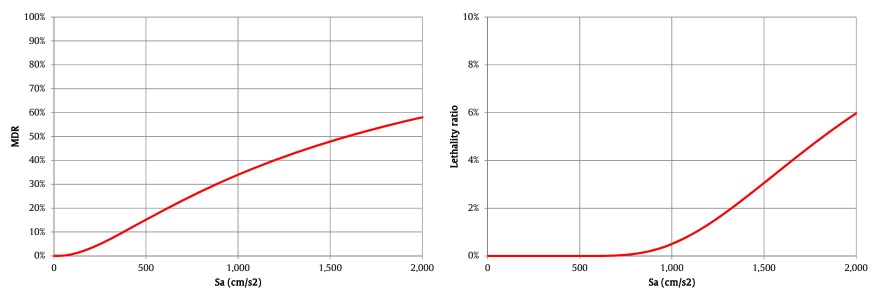


Figure A2-9 Physical (left) and human (right) vulnerability functions for C4L (low code) building class. *MDR*=55%; *LR*=10%

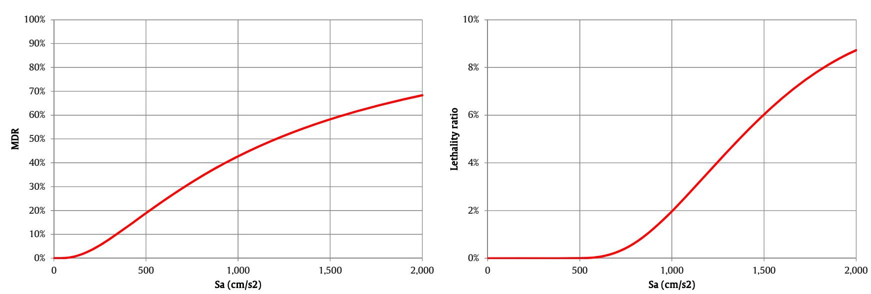


Figure A2-10 Physical (left) and human (right) vulnerability functions for C4M (low code) building class. *MDR*=55%; *LR*=10%

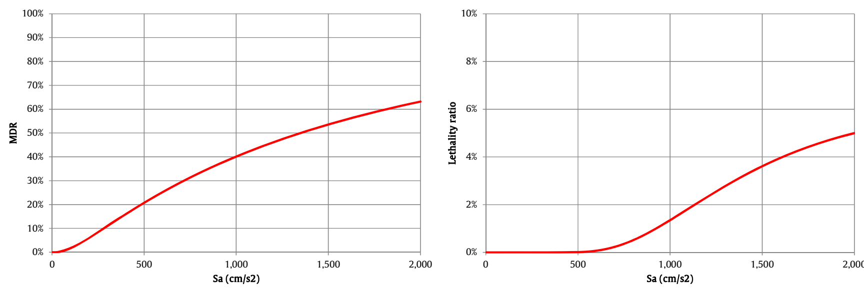


Figure A2-11 Physical (left) and human (right) vulnerability functions for CM1L (low code) building class. *MDR*=50%; *LR*=6%

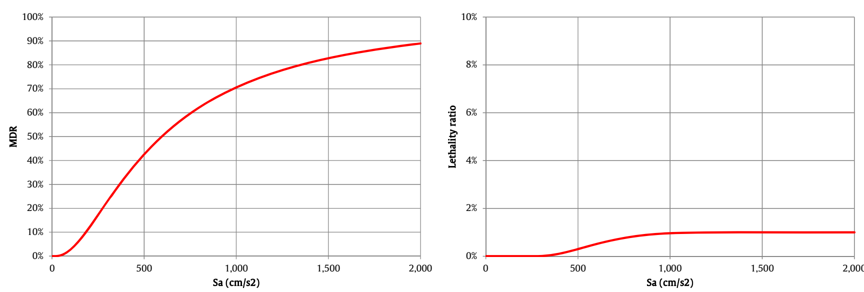


Figure A2-12 Physical (left) and human (right) vulnerability functions for non-engineered building class. *MDR*=50%; *LR*=1%

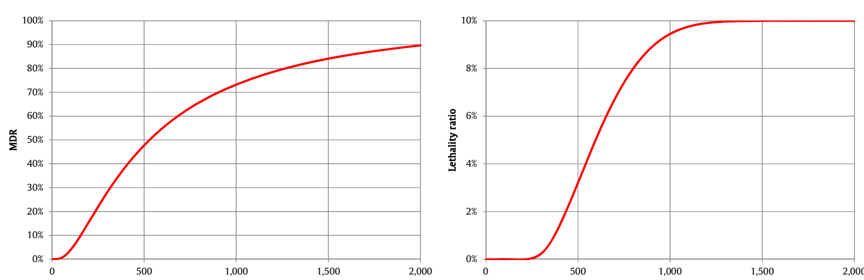


Figure A2-13 Physical (left) and human (right) vulnerability functions for PC1H (low code) building class. *MDR*=55%; *LR*=10%

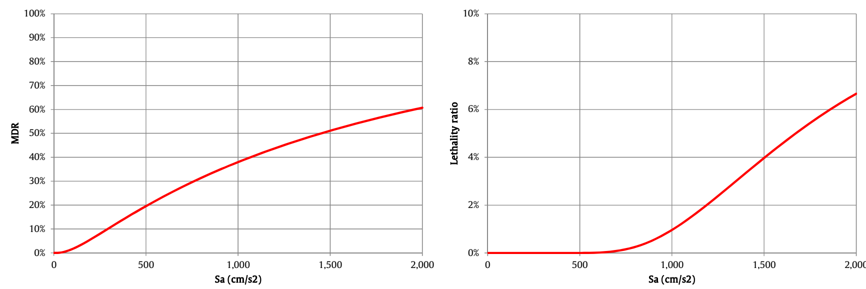


Figure A2-14 Physical (left) and human (right) vulnerability functions for PC1L (low code) building class. *MDR*=55%; *LR*=10%

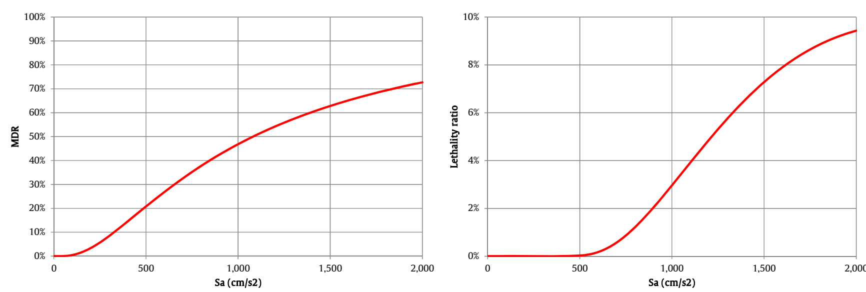


Figure A2-15 Physical (left) and human (right) vulnerability functions for PC1M (low code) building class. *MDR*=55%; *LR*=10%

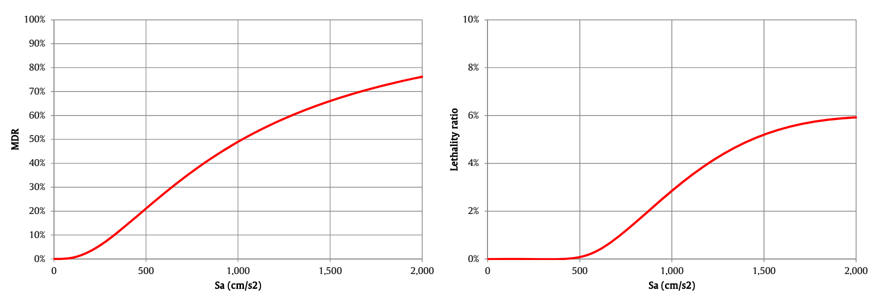


Figure A2-16 Physical (left) and human (right) vulnerability functions for RM1M (medium code) building class. *MDR*=50%; *LR*=6%

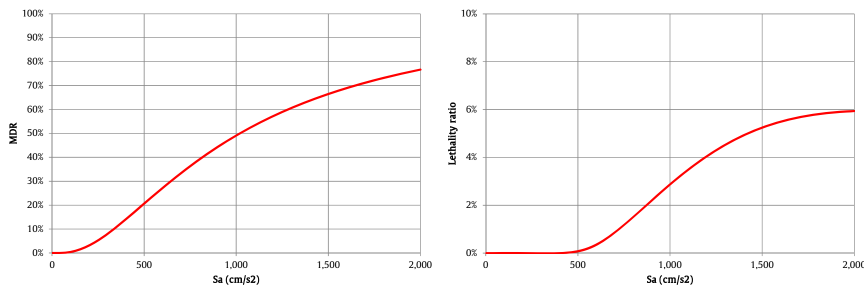


Figure A2-17 Physical (left) and human (right) vulnerability functions for RM2M (medium code) building class. *MDR*=50%; *LR*=6%

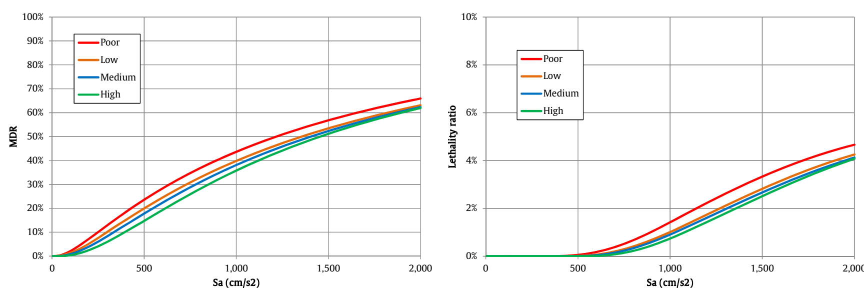


Figure A2-18 Physical (left) and human (right) vulnerability functions for RM2L building class. *MDR*=55%; *LR*=6%

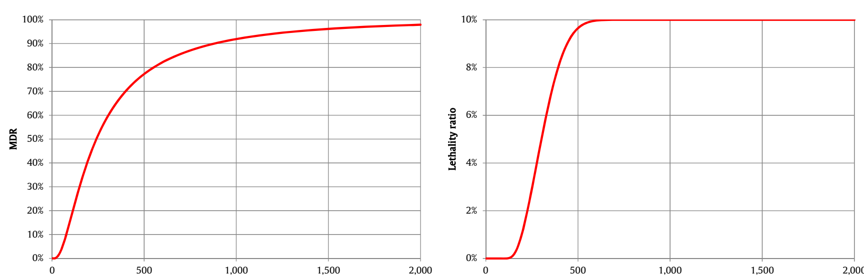


Figure A2-19 Physical (left) and human (right) vulnerability functions for S1H (low code) building class. *MDR*=60%; *LR*=10%

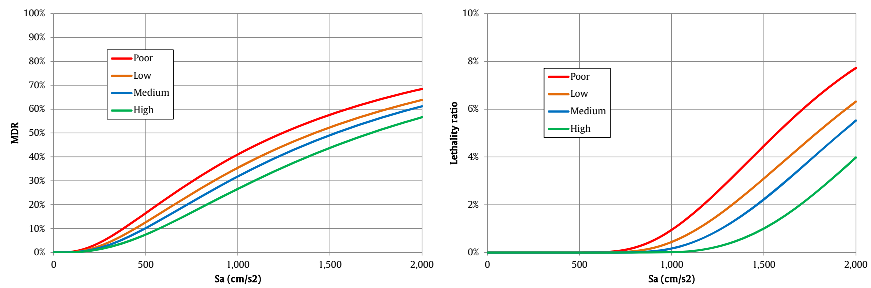


Figure A2-20 Physical (left) and human (right) vulnerability functions for S1L building class. *MDR*=60%; *LR*=10%

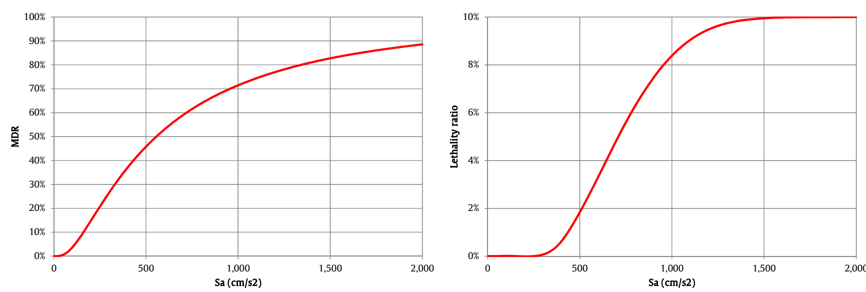


Figure A2-21 Physical (left) and human (right) vulnerability functions for S1M (low code) building class. *MDR*=60%; *LR*=10%

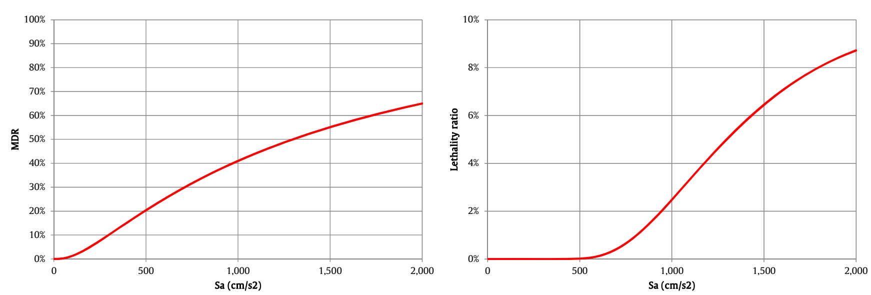


Figure A2-22 Physical (left) and human (right) vulnerability functions for S3 (low code) building class. *MDR*=50%; *LR*=10%

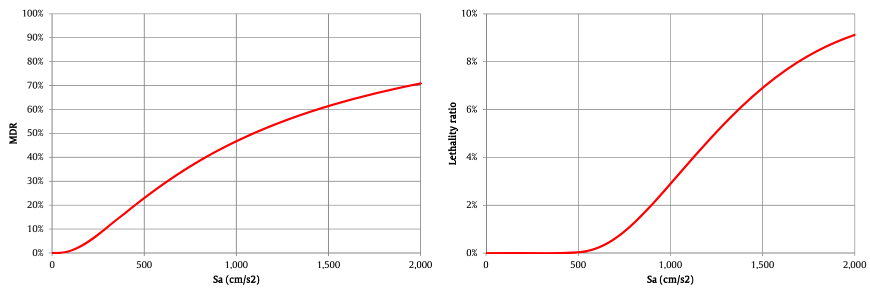


Figure A2-23 Physical (left) and human (right) vulnerability functions for S4M (low code) building class. *MDR*=55%; *LR*=10%

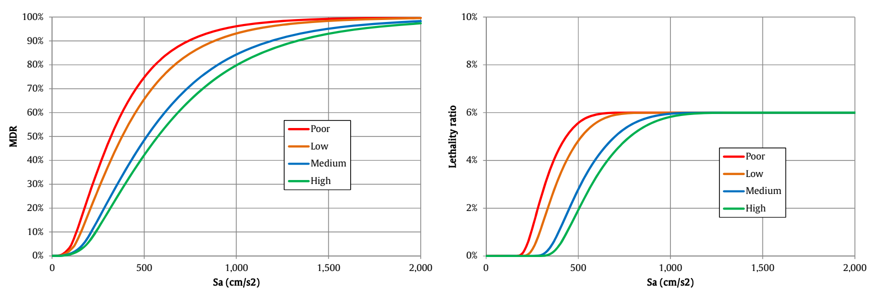


Figure A2-24 Physical (left) and human (right) vulnerability functions for TA1L building class. *MDR*=50%; *LR*=6%

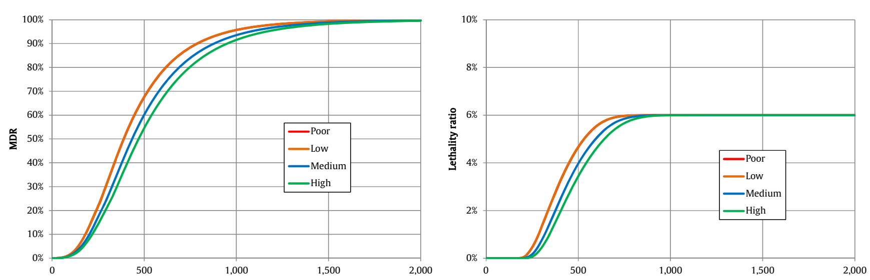


Figure A2-25 Physical (left) and human (right) vulnerability functions for URML building class. *MDR*=50%; *LR*=6%

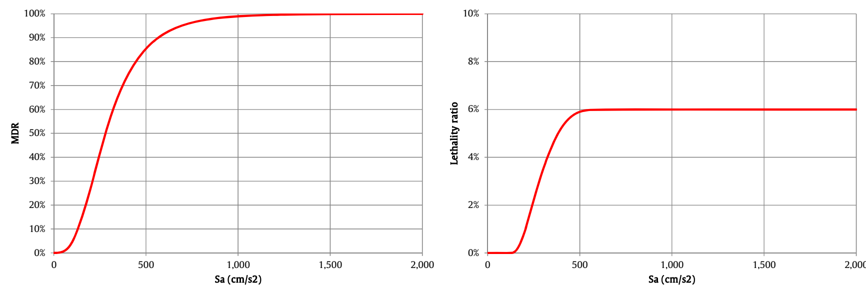


Figure A2-26 Physical (left) and human (right) vulnerability functions for URMM (poor code) building class. *MDR*=50%; *LR*=6%

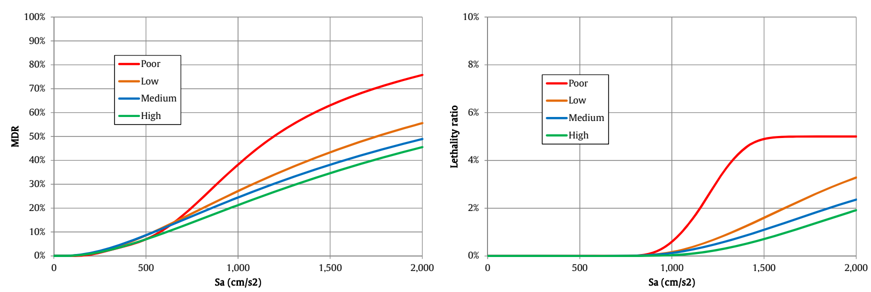


Figure A2-27 Physical (left) and human (right) vulnerability functions for W1 building class. *MDR*=50%; *LR*=5%

Annex 3

PUBLICATIONS AND PROJECTS RELATED TO THE THESIS

During the development of the Ph.D. thesis, a series of related articles in peer-reviewed journals, books and articles in proceedings of national and international conferences and congresses were published. There was also participation in different national and international consultancy projects. A list of the publications and projects is given next.

A3.1 Publications in peer-reviewed journals

- Salgado-Gálvez M.A., Zuloaga D., Velásquez C.A., Carreño M.L., Cardona O.D. and Barbat A.H. (2016). Urban seismic risk index for Medellín, Colombia, based on probabilistic loss and casualties estimations. *Natural Hazards*. 80(3): 1995-2021. DOI: 10.1007/s11069-015-2056-4
- Salgado-Gálvez M.A., Bernal G.A., Barbat A.H., Carreño M.L. and Cardona O.D. (2016). Probabilistic estimation of annual lost economic production due to premature deaths because of earthquakes. *Human and Ecological Risk Assessment*. 22(2): 543-557. DOI: 10.1080/10807039.2015.1095072
- Salgado-Gálvez M.A., Bernal G.A. and Cardona O.D. (2015). Evaluación probabilista de la amenaza sísmica de Colombia con fines de actualización de la Norma Colombiana de Diseño de Puentes CCP-14 (*in Spanish*). *Revista internacional de métodos numéricos para cálculo y diseño en ingeniería*. In press. DOI: 10.1016/j.rimni.2017.07.001
- Salgado-Gálvez M.A., Carreño M.L., Barbat A.H. and Cardona O.D. (2015). Evaluación probabilista del riesgo sísmico en Lorca mediante simulaciones de escenarios (*in Spanish*). *Revista internacional de métodos numéricos para cálculo y diseño en ingeniería*. In press. DOI: 10.1016/j.rimni.2014.12.001
- Salgado-Gálvez M.A., Zuloaga D., Bernal G.A., Mora M.G. and Cardona O.D. (2014). Fully probabilistic seismic risk assessment considering local site effects for the portfolio of buildings in Medellín, Colombia. *Bulletin of earthquake engineering*. 12(2): 671-695.

- Salgado-Gálvez M.A., Zuloaga D., Bernal G.A. and Cardona O.D. (2014). Comparación de los resultados de riesgo sísmico en dos ciudades con los mismos coeficientes de diseño sismo resistente (*in Spanish*). *Revista de Ingeniería*, Universidad de Los Andes. 41:8-14.
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A3.2 Books

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A3.3 Chapters in books

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A3.4 Proceedings in conferences and congresses

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A3.5 Related projects

- Comprehensive probabilistic approach for seismic risk evaluation in Spain (*COPASRE*). Project funded by the Spanish Ministry for Economy and Competitiveness where the observed and modelled damages comparison for Lorca was performed.
- Update and harmonization of the regional Latin America and Caribbean seismic hazard model for the "*Sistema R*". A regional model with continuous sources over the political divisions for Latin American and Caribbean countries was developed.
- Update of the Colombian earthquake resistant bridge building code (CCP-14) where the seismic hazard model used for the estimation of optimum and design coefficients was originally developed. Project developed with the Colombian Association for Earthquake Engineering (AIS).
- Global Assessment Report on Disaster Risk Reduction 2013 and 2015. Project funded by the United Nations office for disaster risk reduction (UNISDR) where a global fully probabilistic multi-hazard risk assessment was performed for more than 200 countries.
- Probabilistic seismic risk assessment of the water and sewage network of Aguas de Manizales. Project funded by the *Universidad Nacional de Colombia* and *Corpocaldas* where using the probabilistic damages and losses framework used in this thesis the estimation of expected losses in different components of the network was performed.
- Disaster risk profiles for Venezuela, Chile and Trinidad and Tobago. Project funded by the Inter-American Development Bank (IDB) where a probabilistic seismic hazard model was developed to generate a set of stochastic earthquake scenarios.
- Update of the indicators of disaster risk and risk management. Project funded by the Inter-American Development Bank (IDB) where the Disaster Deficit Index (DDI) incorporated a probabilistic approach for the estimation of probable maximum losses for different mean return periods.
- GEM Earthquake consequences database. A review of damages, losses and casualties for different earthquakes in Latin America was performed and the results included in the final database. (www.gemecd.org).
- Seismic microzonation of the urban area of Quito, Ecuador. Project funded by the *Municipio del Distrito Metropolitano de Quito* where a probabilistic seismic hazard assessment was developed as input data for the dynamic soil response assessment at different locations.

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