From Earthquake Risk to Earthquake Insurance

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Abstract: The assessment of earthquake and risk, on an urban or regional scale, constitutes an important element in the mitigation of economic and social losses due to earthquakes, planning of immediate post-earthquake actions as well as the development of earthquake insurance schemes. Earthquakes also create contingent liabilities for governments for recovery and an expedient return to normalcy. Earthquake insurance assists in the management of the financial impacts of earthquake risk and public earthquake insurance schemes have been established in several countries. Earthquake risk assessment models are in the insurance industry to support informed decisions and pricing for earthquake insurance and reinsurance. Earthquake loss and risk assessment models consider and combine three main elements: earthquake hazard, fragility/vulnerability of assets and the inventory of assets exposed to hazard. Challenges exist in the characterization of the earthquake hazard as well as in the determination of the fragilities/vulnerabilities of the physical and social elements exposed to the hazard.

Keywords: Earthquake, risk, insurance

1. Introduction

Earthquakes are one of the most destructive natural perils and can lead to severe economic, social and environmental impacts. Rapid urbanization and the accumulation of assets in seismic areas have led to an increase in earthquake risk in many parts of the world.

In UNISDR terminology, “Risk” is defined as “the combination of the probability of an event and its negative consequences”, and “Risk assessment” is defined as “a methodology to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment in which they depend”.

Earthquake risk can be defined as the probable economic, social and environmental consequences of earthquakes that may occur in a specified period of time and is determined by using earthquake loss modeling procedures. In this context, the loss is the reduction in the value of an asset due to earthquake damage and risk is the quantification of this loss in terms of its probability (or uncertainty) of occurrence. In simpler terms, the “loss” is the reduction in the value of an asset due to damage and the “risk” represents the uncertainty of this “loss”

Public and private enterprises analyze their portfolio of assets to assess and manage their earthquake risk. In calculating the earthquake risk of each asset, social and economic losses, due to not only physical damage to buildings and facilities but also to the non-structural damage, consequential damage and business interruption are considered. In insurance terminology, these risk assessments and estimations are called “Catastrophe (or simply, Cat) Modeling”. Insurance companies use these cat models for insurance pricing, portfolio management, to monitor their capital requirements and solvency and to determine their reinsurance needs.

For a given inventory of elements (location and physical characteristics) exposed to seismic hazard, the important ingredients of this earthquake risk estimation flowchart are Ground Motion, Direct Physical Damage, Induced Physical Damage, and Direct/Indirect Socio-Economic Losses.

Almost all earthquake risk assessment schemes rely on the quantification of the earthquake shaking as intensity measure parameters using probabilistic or deterministic earthquake hazard models. For a given ground motion (intensity measure) the direct physical damage is determined by the fragility/vulnerability relationships that provide the probability of damage/loss, conditional on the level of intensity measure. Each step of the process incorporates stochastic or random variation associated with all aspects of the modeled phenomenon. Consequently, the earthquake risk estimations should consider the uncertainties in these steps.

In 1990, under the UN-IDNDR (International Decade for Natural Disaster Reduction) program the RADIUS (Risk Assessment Tools for the Diagnosis of Urban Areas against Seismic Disasters) project promoted the earthquake risk assessment and mitigation in the international scale (UNISDR, 2000). One of the most used methodologies of earthquake risk assessment originate from HAZUS (www.fema.gov/hazus) where, HAZUS-MH MR4 is a damage- and loss-estimation software developed by FEMA to estimate potential losses from natural disasters. The World Bank's CAPRA (http://www.ecapra.org/) project has also developed the widely used probabilistic risk assessment tools and software. Besides, several European Projects have also contributed to the development of comprehensive methodologies and tools for earthquake-risk assessment.

The Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA, http://www.sera-eu.org/en/home/) as a Horizon 2020-supported program, works to develop a comprehensive framework for seismic risk modelling at European scale. This risk modeling involves: European capacity curves, fragility, consequence and vulnerability models; European seismic risk results in terms of average annual loss (AAL), probable maximum loss (PML), and risk maps in terms of economic loss and fatalities for specific return periods and; Methods and data to test and evaluate the components of seismic risk models.

GEM initiative (www.globalquakemodel.org), which started in 2006 to develop global, open-source earthquake risk assessment software and tools, has contributed profoundly to the earthquake hazard and risk assessment standards, developed guidelines, the OpenQuake (www.globalquakemodel.org/openquake) software and the global earthquake hazard and risk maps (https://www.globalquakemodel.org/gem).

2. Earthquake Risk Assessment Models

The estimation of the earthquake risk due to deterministic earthquake scenarios is of use for communicating seismic risk to the public and to decision makers. However, a probabilistic assessment of earthquake risk (generally called, Probabilistic Seismic Risk Analysis-PSRA) is needed for risk prioritization, risk mitigation actions and for decision-making in the insurance and reinsurance sectors.

Since the PSRA encompasses multitude sources of uncertainties stemming from hazard, inventory and vulnerability (or fragility and consequence) functions, Monte Carlo simulations are routinely employed to facilitate the orderly propagation of these uncertainties within the process. Such event-based simulation involves suites of probabilistically characterized deterministic risk scenarios (e.g. Crowley and Bommer 2006, Silva et al. 2013).

Similar to PSHA, the results of a PSRA can also be deaggregated to identify the components of the overall system (i.e. earthquake scenarios) that are contributing significantly to the seismic risk (e.g. Goda and Hong, 2008; Jayaram and Baker, 2009).

One of the first rational assessment of earthquake risk is carried out by Whitman et al. (1973) using MMI versus Damage Ratio matrices. Similar studies in USA led to the development of HAZUS (FEMA, 2003) Some of the open access and state-of-the-art software packages for earthquake risk assessment can be listed as follows:

• CAPRA GIS- Earthquake module, http://www.ecapra.org/software
•EQRM,http://www.ga.gov.au/scientific-topics/hazards/earthquake/capabilties/modelling/eqrm
• ERGO (MAEviz/mHARP), http://ergo.ncsa.illinois.edu/?page id=48
• HAZUS-MH earthquake module, http://www.fema.gov/hazus
• OpenQuake, https://www.globalquakemodel.org/openquake/
• ELER, http://www.koeri.boun.edu.tr/Haberler/NERIES%20ELER%20V3 .1 6 176.depmuh
• RiskScape-Earthquake, https://riskscape.niwa.co.nz/
• SELENA, http://www.norsar.no/seismology/engineering/SELENA-RISe/
• EQVIS, http://www.vce.at/SYNER-G/files/downloads.html

The OpenQuake Engine (https://www. globalquakemodel.org/)is GEM 's state-of-the-art software for seismic hazard and risk assessment at varying scales of resolution, from global to local. It is open-source, fully transparent and can be used with GEM or user-developed models to carry out scenario-based and probabilistic hazard and risk calculations and produce a great variety of hazard and loss outputs. Spatial correlation of the ground motion residuals and correlation of the uncertainty in the vulnerability can be modeled. Main calculations performed in connection with the earthquake loss assessment can be listed as: Scenario risk; Scenario damage; Classical PSHA-based risk; Probabilistic event-based risk and; Retrofitting benefit-cost ratio. Comprehensive global earthquake risk maps were provided by GEM (https://www.globalquakemodel.org/gem).

Today, the seismic risk/loss assessment can be essentially grouped under the following three approaches (Silva et al., 2013 and 2014):

• Deterministic Risk/Loss Calculation (analysis due to a single earthquake scenario);
• Probabilistic Risk/Loss Calculation (an analysis that considers a probabilistic description of the earthquake events and associated ground motions) and;
• Classical PSHA-Based Risk/Loss Calculation (analysis based on conventional probabilistic earthquake hazard assessment)

3. Metrics Used in Earthquake Risk Assessment related to Earthquake Insurance

For the measurement of risk for a single asset or portfolio of assets, several metrics, in physical and financial loss terms, are used. Following is a brief explanation of these metrics.

The Loss Exceedance (or Exceedance Probability, EP) curves, the Average Annual Loss (AAL) and Probable Maximum Loss (PML) constitute the important metrics of the risk/loss assessment. In engineering terms, the losses associated with the building stock are generally quantified in terms of Los Ratio (LR), defined as the repair cost divided by the replacement cost. LR is also called as the damage factor, damage ratio and fractional loss.

Loss Exceedance Curves (EP Curves) describe losses versus probability of exceedance in a given time span (generally, annual). EP Curves are used for cat modelling, as it is beneficial to identify attachment or exhaustion probabilities, calculate expected losses within a given range, or to provide benchmarks for comparisons between risks or over time.

Occurrence Exceedance Probability (OEP) is the probability that the associated loss level will be exceeded by any event in any given year. It provides information on losses assuming a single event occurrence in a given year. Aggregate Exceedance Probability (AEP) is the probability that the associated loss level will be exceeded by the aggregated losses in any given year. It provides information on losses assuming one or more occurrences in a year.

The AEP and OEP can be used for managing exposure both to single large event or to multiple events across a time period. They can be similar when the probability of two or more events is very small; they are identical when there is zero probability of two or more events. However, AEP can be very different from the OEP when the probability of two or more events is significant.

Value at Risk (VaR) is equivalent to the Return Period, and measures a single point of a range of potential outcomes corresponding to a given confidence.

Tail Value at Risk (TVaR) measures the mean loss of all potential outcomes with losses greater than a fixed point. When used to compare two risks, along with mean loss and Value at Risk, it helps communicate how quickly potential losses tail off.

VaR and TVaR are both mathematical measures used in cat modelling to represent a risk profile, or range of potential outcomes, in a single value.

Average Annual Loss (AAL) (or Annual Estimated Loss - AEL) is the expected value of a loss exceedance distribution and can be computed as the product of the loss for a given event with the probability of at least one occurrence of event, summed over all events. AAL is the average loss of all modeled events, weighted by their probability of annual occurrence (EP curve) and corresponds to the area underneath the EP curve. If the loss ratio (LR) is used for the quantification of loss, then the term Average Annual Loss Ratio (AALR) is used in lieu of AAL. For earthquake insurance purposes, the AAL or AALR is of particular importance in determining the annual pure premiums.

Pure Premium represents the average of all potential outcomes considered in the analysis, and could be considered to be the break-even point if such a policy is to be written for very large number of times.

The Probable Maximum Loss (PML) is one of the most popular metrics in financial risk management, and there are several definitions. Conventionally, it was defined as a fractal of the loss corresponding to the return period of 475 years. In Japan, the PML is defined as the (conditional) 0.9-fractile value for a scenario that corresponds to a selected probability level (typically, return period of 475 years).

ASTM E2026-16A use specific nomenclatures for seismic risk assessment of buildings. are in use: Scenario Upper Loss, based on deterministic analysis) (SUL) is defined as the earthquake loss to the building with a 90 percent confidence of non-exceedance (or a 10 percent probability of exceedance), resulting from a specified event on specific faults affecting the building. If the specified earthquake hazard is the 475-year return period event, then this term can be called the SUL475, and this term is the same measurement as the traditional PML defined above. Scenario Expected Loss, based on deterministic analysis, (SEL) is defined as the average expected loss to the building, resulting from a specified event on specific faults affecting the building. If the specified earthquake is the 475-year return period event, then this term can be called the SEL475. The Probable Loss, based on probabilistic analysis, (PL) is defined as the earthquake loss to the building(s) that has a specified probability of being exceeded in a given time period from earthquake shaking. The PL is commonly taken as the loss that has a 10 percent probability of exceedance in 50 years, which is called the PL475, because it corresponds to a return period of 475 years.

4.Probabilistic Earthquake Risk Calculation

In the Probabilistic Loss Calculation process the probability of losses and loss statistics are computed using Monte-Carlo simulations, based on stochastic event sets and associated ground motion fields. The flowchart of the process is shown in Fig. 1. For the realistic calculation of the ground motion field for each event, the sampling of the inter-event variability and the spatial correlation of the intra-event residuals of the ground-motion model should be considered. The set of ground-motion fields are combined with the exposure and vulnerability model to obtain losses. For the computation of the loss exceedance curve: the cumulative histogram, built using the list of losses per asset (of a given typology) in selected bins of loss over the time span, can be considered. An aggregated loss curve, representative of the whole set of assets within the region (or portfolio) can be obtained by aggregating all the losses.

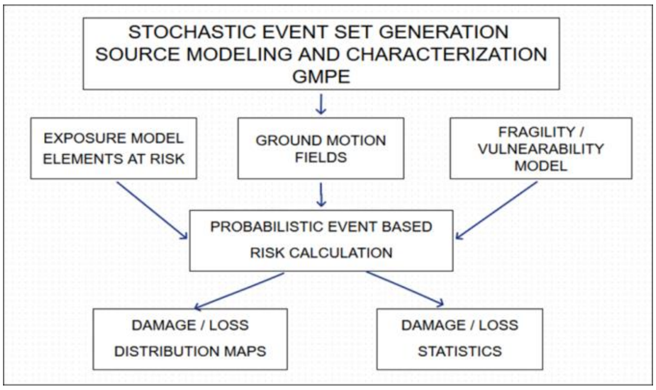
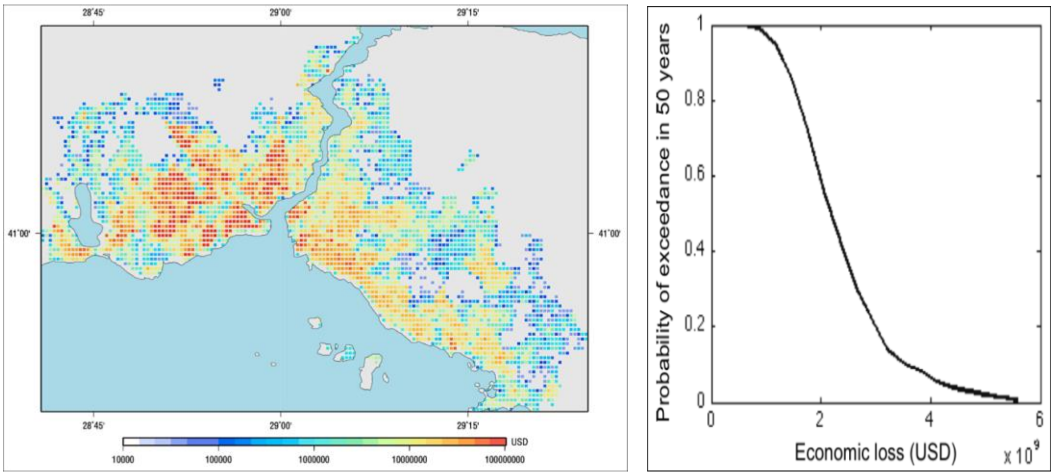


Figure 1. Simplified flowchart of the Probabilistic Loss Calculation process

Following are some earthquake risk assessment examples, where, probabilistic earthquake loss calculation procedure is used.

<u>Probabilistic Earthquake Risk Assessments for İstanbul</u>

Using GEM OpenQuake Probabilistic Loss Calculation process, Crowley et al. (2011) present (respectively in Figures 2 a and b) a loss map and a total loss exceedance curve for a probability of exceedance of 10% in 50 years for reinforced concrete buildings located in the metropolitan area of Istanbul.



Figures 20 a and b. Loss map and loss exceedance curve for a probability of exceedance of 10% in 50 years for reinforced concrete buildings located in the metropolitan area of Istanbul (Crowley et al.,2011)

Akkar et al. (2016) have computed the earthquake losses in central Istanbul using the probabilistic loss calculation process. The earthquake risk was assessed using intensity-based fragility relationships of Lagomarsino and Giovinazzi (2006), where the instrumental intensities were computed using the Akkar and Boomer (2010) and Akkar et al. (2014) -based PGA and PGV values. Figure 2 a and b show probability exceedance of very heavy damage state (DS4 in EMS'98) in 50 years for post-2002 low-rise RC buildings erected after 2002.

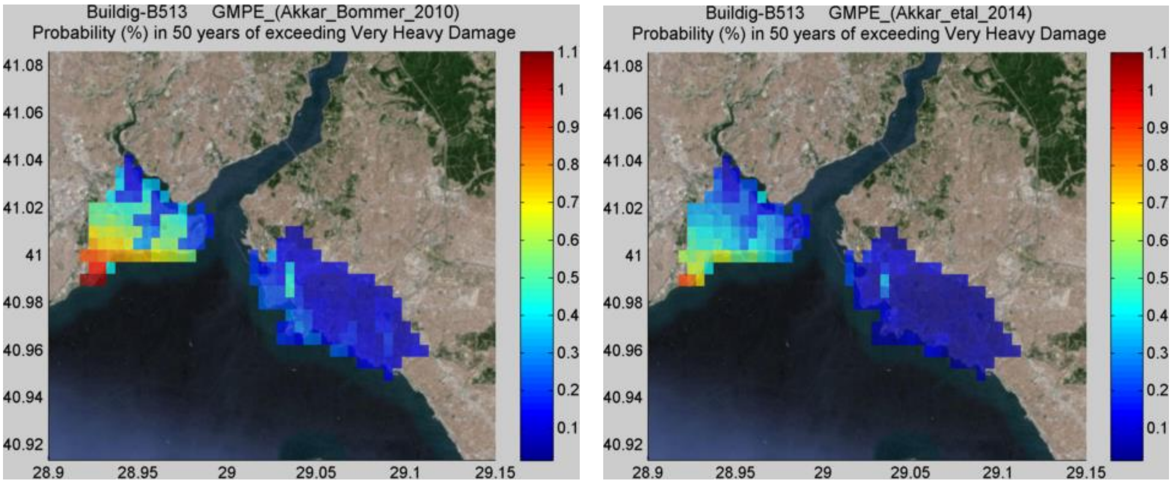


Figure 2 a, b. Probability exceedance of very heavy damage state (DS4 in EMS'95) in 50 years for post-2002 low-rise RC buildings built after 2002. Akkar and Boomer (2010) (a) and Akkar et al. (2014) (b) GMPMs are used.

5.Classical PSHA-Based Earthquake Risk Calculation

In this approach, classical PSHA assessment (Cornell, 1968; McGuire, 2004) can be used to calculate loss exceedance curves for single assets, calculated site by site, on the basis of hazard curves. The flowchart of the process is shown in Figure 3. Discrete vulnerability functions are converted into a loss exceedance matrix (e.g. a matrix which describes the probability of exceedance of each monetary loss value or loss ratio for a discrete set of intensity measure levels). The values of each column of this matrix are multiplied by the probability of occurrence of the associated intensity measure level, extracted from the hazard curves. To compute the loss exceedance curve: the probabilities of exceedance of the loss (or the loss ratio) curve are obtained by summing all the values per loss (or loss ratio).

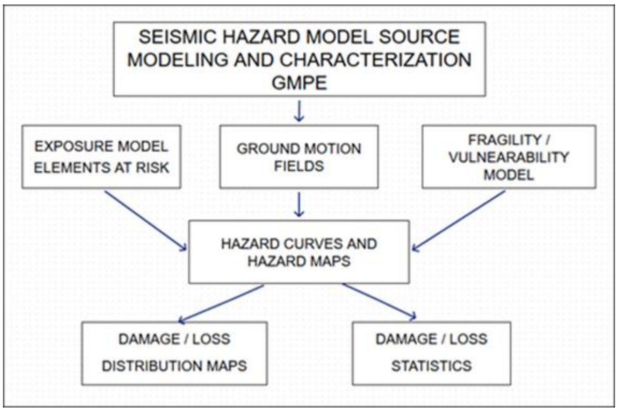


Figure 3. Simplified flowchart of the Classical PSHA-Based Loss Calculation

Demircioğlu et.al (2012) has computed the grid-based building damage distributions, Loss Ratios (LR) and Average Annual Loss Ratios (AALR) corresponding to 72, 475, and

2475-year average return periods. Figure 4 provides sub-province based LR values for Turkey for the 475-year average return period. In Figure 5 the sub-district based AAL values are shown.

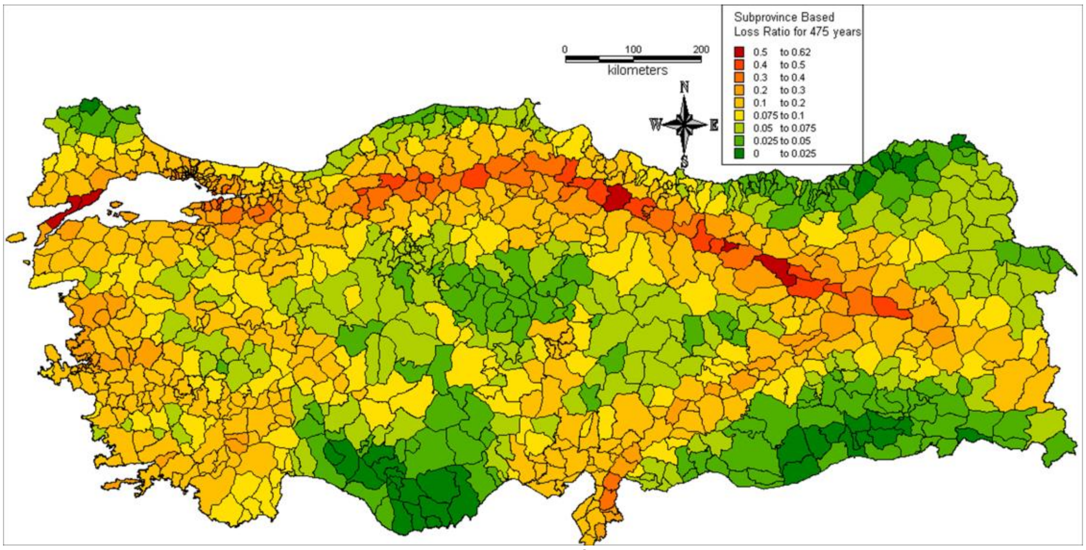


Figure 4. Sub-province based loss ratios for 475-year average return period

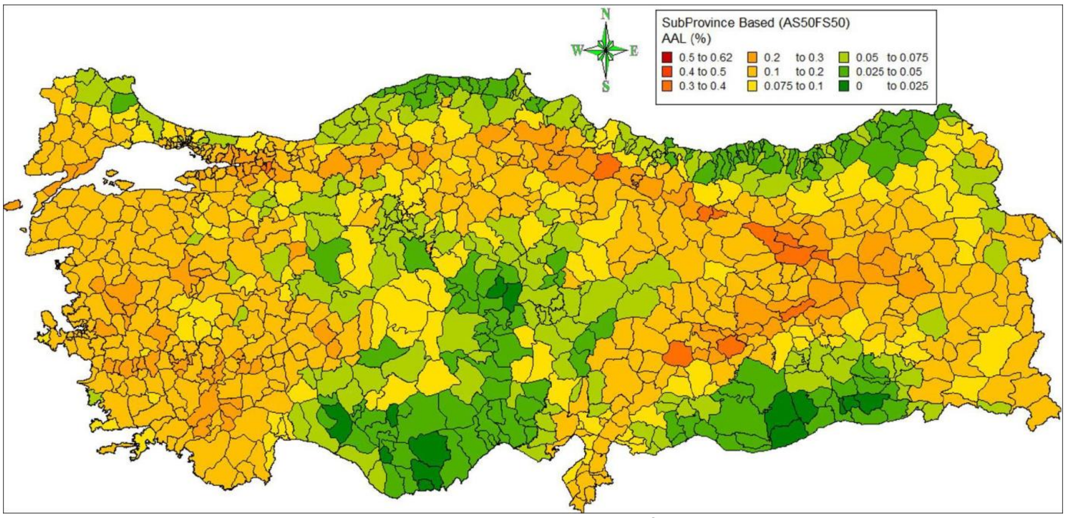


Figure 5. Sub district-based Annual Average Loss Ratios for Turkey (Demircioğlu et.al, 2012)

6. Uncertainties in Risk Assessments

The main sources of uncertainties in earthquake risk assessment are:

• Hazard uncertainty (seismic source characterization and ground motion modeling)
• Vulnerability uncertainty
• Uncertainty in the assumptions and specifications of the risk model
• Portfolio uncertainty (location and other attributes of the building classes)

In general, there exist two types of uncertainties that need to be considered in earthquake risk/loss assessments: aleatory and epistemic. Aleatory uncertainty accounts for the randomness of the data used in the analysis and the epistemic uncertainty accounts for lack of knowledge in the model. Aleatory variability, that generally affects the loss distributions and exceedance curves is directly included in the probabilistic analysis calculations through the inclusion of the standard deviation of a GMPM considered in the analysis. Epistemic uncertainties, which can increase the spread of the loss distributions, are generally considered by means of a logic tree formulation with appropriate branches and weights associated with different hypotheses. Similarly, Monte-Carlo techniques can also be used to examine the effect of the epistemic uncertainties in loss estimates.

Fig. 7 (after Wong et al, 2000) illustrates the effect of uncertainties on loss estimation. Uncertainties arise in part from incomplete inventories of the built environment, inadequate scientific knowledge of the process, earthquake ground motion (IMs) and their effects upon buildings and facilities (fragility/vulnerability relationships). The reliability of the fragility/vulnerability relationships is essentially related to the conformity of the ground motion IMs with the earthquake performance (damage) of the building inventory. These uncertainties can result in a range of uncertainty in loss estimates, at best, a factor of two. The general finding of the studies on the uncertainties in earthquake loss estimation is that the uncertainties are large and at least as equal to uncertainties in hazard analyses (Stafford et al., 2007; Strasser et.al, 2008). It should also be noted that the estimates of human casualties are derived by uncertain relationships from already uncertain building loss estimates, so the uncertainties in these estimates are rather compounded (Coburn and Spence, 2002).

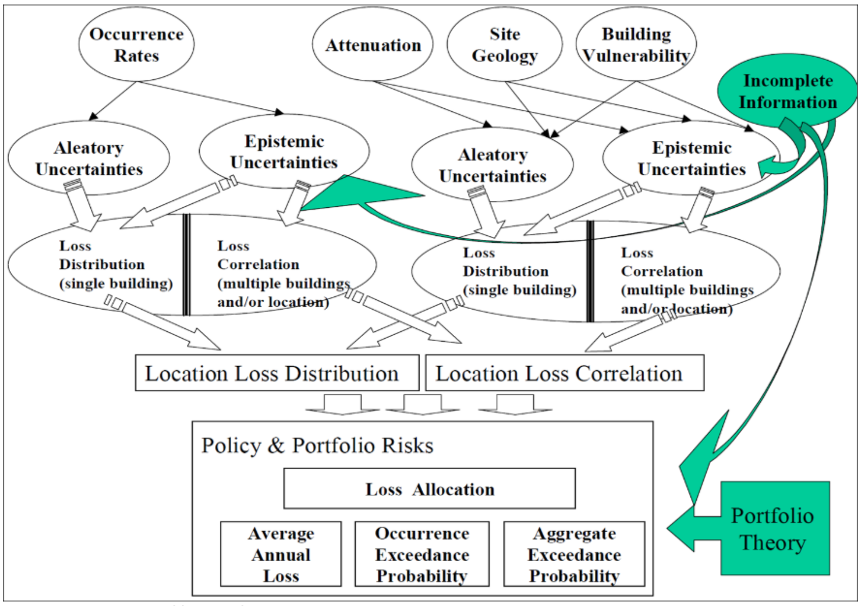


Figure 6. Effect of Uncertainties on Loss Estimation (Wong et al, 2000)

7. Conclusions

Earthquake risk and loss assessment is needed to prioritize risk mitigation actions, emergency planning, and management of related financial commitments. The insurance sector has to conduct the earthquake risk and loss analysis of their portfolio to assess their solvency in the next major disaster, to price insurance, and to buy reinsurance cover.

Due to the research and development on rational probabilistic risk/loss assessment methodologies and studies conducted ın connectıon with several important projects, today we have substantial capability to analyses the risk and losses ensuing from low-probability, high consequence major earthquake events.

In this regard, the selection of appropriate ground motion models, that are compatible with the regional seismo-tectonic characteristics, and the selectıon of vulnerability (or fragility and consequence) relationships that are compatible with the IMs and appropriate wıth the inventory of assets ın the portfolio are of great importance. The mean damage ratio is highly sensitive to the consequence models (i.e. loss ratios assigned to each damage state).

The probability distribution function for the loss to a portfolio depends on the spatial correlation of the ground motion and the vulnerability of the buildings. The consideration of the spatial correlatıon does not change the mean loss but increases the dispersion in the loss distribution, which can have a profound influence on loss and insurance-related decisions. When spatial correlation is considered, the losses at longer return periods increase. On the opposite side, the losses at shorter return periods may be overestimated if the spatial correlation is not included in the analysis.

The reduction of the uncertainties in earthquake risk/loss assessment is an important issue to increase the reliability and to reduce the variability between the assessments resulting from different earthquake risk/loss models. In this connection, earthquake risk/loss assessment models should explicitly account for the epistemic uncertainties in the components of analysis, especially in the inventory of assets and vulnerability relationships.

The practice of earthquake risk and loss assessment is now established. However, a number of research issues, such as: uncertainty correlation in vulnerability, logic-tree modeling of epistemic uncertainties, and treatment of uncertainties in exposure modeling, remain for treatment in future applications.

New earthquake insurance products based on parametric indexing are being emerged. These insurance products could further improve the efficiency earthquake insurance pools by making them more attractive to individuals, thereby scaling up their contribution to building resilience.

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