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Evaluation of earthquake mitigation measures to reduce economic and human losses: a case study to residential property owners in the metropolitan area of Shiraz, Iran

Mehdi Sadeghi[1] · Stefan Hochrainer-Stigler[2] ·
Mohsen Ghafory-Ashtiany[3]

Abstract Iran is located in a highly seismic active region, and building structures, therefore, need to be designed and constructed to withstand major earthquakes. Structural mitigation measures are now seen as one key element to reduce economic as well as human losses for today and in the future. However, the costs and benefits of various options are difficult to be assessed and usually done without considering both human and economic aspects. This paper should fill part of this gap and performs an in-depth earthquake risk analysis for Shiraz city, in Iran. Additionally, the effects of different mitigation measures for buildings and corresponding changes in risk levels have been investigated. Probabilistic seismic hazard analysis is used to prepare the hazard curves, to be used in the probabilistic cost-benefit analysis of buildings to investigate the effects of using different strengthening strategies. Regarding the importance of the assessment of human casualties during earthquakes, additional cost-benefit ratios were calculated by considering the value of statistical life and performing sensitivity analysis. The results show that considering the value of statistical life in cost-benefit analysis can significantly increase the structural cost-benefit ratios. This has important implications for the decision support as well as policy making side in Iran, and we conclude with suggestions how these issues could be addressed in the future using a risk-layering approach.

Keywords Earthquake risk · Probabilistic seismic hazard analysis · Cost-benefit analysis · Human loss · Value of statistical life · Shiraz · Iran

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✉ Mehdi Sadeghi
Mehdisadeghi84@gmail.com

[1] Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

[2] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

[3] International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran

1 Introduction

As experienced in the recent past, e.g., the Tohoku earthquake in 2011, in Haiti in 2010, in China in 2008, and most recently in Nepal in 2015, earthquake events can be devastating, with a large number of casualties and economic losses. Similar to the case of weather-related risks also for earthquake risks, one key element for a sustainable disaster risk management strategy is the accurate assessment of potential future losses, corresponding event probabilities and capacities to cope with them (GAR 2011; IPCC 2012). To assess risk on various levels and to adapt to changes in risk, iterative loss estimation and management play a vital role as property values change over time, as do the costs of repair and replacement, also building materials, design and practice change along with new building codes. Therefore, new structures may be more or less vulnerable to catastrophe events than existing ones which has to be taken into account in future planning (Grossi and Kunreuther 2005). The need to proactively engage in dealing with (extreme) risks is now featured prominently in publications on global assessments of risks and development. For example, the World Development Report (2014) emphasizes the need to shift from unplanned and ad hoc responses to proactive and systematic risk management. The Global Risks Report published by the World Economic Forum (2014) concludes that better efforts are needed to understand, measure and foresee the evolution of interdependencies (of risk). Finally, the recent Global Assessment Reports (GAR 2011, 2015) issued a stark warning that economic losses linked to disasters are "out of control" and will continue to escalate unless disaster risk management becomes a core part of business investment strategies and call for higher investment in risk reduction strategies.

However, to deal with extremes in a proactive manner, they have to be assessed on a forward looking basis (Kull et al. 2013). Generally speaking, disaster risk is a function of the hazard, the vulnerability and the exposed elements, and changing each of these dimensions also will change the risk (Lugeri et al. 2010). Physical or structural risk management measures are usually focusing on decreasing the level of hazard or reducing the level of vulnerability of the exposed elements. Which types of structural measures have to be actually applied very much depends on the type of hazard. While for earthquakes and hurricanes, mitigation usually focuses on the vulnerability of the exposed components, for hazards, such as tsunamis or volcanic hazards, the measures to reduce risk are oriented toward land use planning. Finally, for hazards which depend very much on local conditions, such as flooding or landslides, measures may be oriented toward hazard reduction, e.g., via dikes or embankments (ERN-AL 2011). As indicated, economic evaluation of vulnerability reduction through physical interventions can be performed via cost-benefit analysis. Such kind of analysis can be done for different kind of hazards (see for a discussion Mechler 2005) and usually involves a detailed analysis of the underlying risk as well as the assessment of costs and benefits of structural mitigation options (Michel-Kerjan et al. 2012).

We aim in the same direction and present a catastrophe modeling approach which is based on a probabilistic seismic hazard analysis (PSHA) method and uses high-precision spatial data of exposed assets. Based on these direct earthquake risk assessment results, we perform afterward a (probabilistic) cost-benefit analysis (CBA) taking explicitly the whole range of possible hazard events into account. The analysis is extended so that not only the reduction in direct damages is taken care of but human losses are considered too. The latter dimension is especially important not only for private sector households, but also for the government, which usually acts as an insurer of last resort as well as having the (moral) obligation to protect the lives of their citizens (see for example the early work of Beatley

1989). The focus will be on Iran, one of the most earthquake-prone areas in the world, where the government is a key risk bearer and plays an important role in compensating losses from the private sector as well as enforcing building codes. Iran itself is highly exposed to earthquake hazards and experienced major earthquakes in the last decades, including Manjil-Roudbar in 1990, Bam in 2003, and Azarbaijan in 2012. All of them have destroyed and damaged many buildings and caused exceptionally high losses both in human and economic terms. For indication purposes, Table 1 summarizes the major earthquake events in Iran since 1990, including the number of deaths, injuries as well as direct economic losses for each event.

For our specific analysis, we focus on district 1 of Shiraz city. It is located in Fars province in southwestern of Iran with a total population of around 1.5 million people (Statistical Center of Iran 2013 and Shiraz Municipal Yearbook 2013). It is seismically located in the Zagros tectonic region, which has a high level of earthquake hazard risk. The building taxonomy of the city shows that it contains a rich mixture of old and new structures with various building types. No earthquake risk and probabilistic cost-benefit analysis were performed yet in this region, and our study should fill part of the information gap on earthquake risk here. Furthermore, effects of physical mitigation measures in terms of reduced economic and human losses will show which options for which building groups would bring the most in terms of general reduction in risk. The inclusion of human losses in the benefit-cost analysis has not been done yet for Iran and should open new avenues about how to deal with future earthquake risks. Based on this analysis, policy recommendations are given and a risk-layer approach suggested how to go forward in this area to build a more earthquake resilient society.

2 Methods and material

A probabilistic approach is the most appropriate way to handle the abundant sources of uncertainty inherent in all natural hazard-related phenomena (Grossi and Kunreuther 2005; Kull et al. 2013). Loss assessments and cost-benefit estimations for mitigation actions are nowadays adopted for a range of different hazards and scales. For example, Mansouri et al.

Table 1 Number of deaths, injuries and direct economic losses of Iran's major earthquakes since 1900

Earthquake events	Magnitude	Date	Human losses		Direct economic loss (million $)
			Deaths	Injuries	
Manjil-Roudbar	7.1	1900	15,000	29,654	3,505
Bejnord	6.1	1996	90	260	99
Ardebil	5.5	1996	980	2,600	145
Ghaen-Birjand	7.3	1997	1,567	3,500	280
Chngoore (avaj)	6.2	2002	230	1,466	65
Bam	6.5	2003	31,828	17,500	2,995
Azarbaijan	6.4	2012	300	3,000	894

Source: Adapted and expanded from Ghafory-Ashtiany (2010) and Pakdel-Lahiji et al. (2014)

(2010) studied the selection and development of structural vulnerability functions and risk algorithms in order to upgrade the seismic risk model for Tehran to include risk management strategies. Motamed et al. (2012) described the development of an automated model of Tehran that uses the output of existing earthquake estimation methodologies which should support decision makers in the planning of appropriate strategies in order to mitigate socioeconomic losses of earthquakes in urban settlements. Hochrainer-Stigler et al. (2011) examined the benefits and costs of improving or retrofitting residential structures in highly exposed low- and middle-income developing countries. Sadeghi (2013) performed probabilistic cost-benefit analysis for one of the Iran's cities considering HAZUS vulnerability functions. Pomonis and Gaspari (2013) have estimated the vulnerability of the post-retrofit buildings in order to assess the potential reduction in economic and human losses in Pylos, Greece. Smyth et al. (2004) have focused on the cost-benefit of earthquake mitigation measures for Turkey apartment houses (for a general discussion, see also Kull et al. 2013). It should be mentioned that usually the focus in CBA is on direct losses such as physical damage to infrastructure, buildings or agricultural assets and less on indirect losses. The latter also includes losses that are not caused by the disaster itself, but by its consequences and can include losses due to business interruption, or increase in diseases or long-term injuries, to name but a few. That indirect loss can be profound, sometimes even higher than the direct losses, and is already acknowledged in the literature (Hallegatte and Przyluski 2010); however, indirect losses are very difficult to be estimated, especially in a risk-based setting and therefore usually neglected in most CBAs.

Regarding the modeling approach which will describe economic and human losses related to seismic hazards, we apply two methodologies: earthquake risk modeling and probabilistic cost-benefit analysis (CBA). Earthquake risk modeling has been designed and implemented based on four main modules: hazard, exposure, vulnerability and loss (Fig. 1).

In more detail, the hazard module characterizes the risk of earthquake hazard by defining the earthquake epicenter location and moment magnitude, along with other relevant parameters. The exposure module in the model describes the inventory or portfolio of properties at risk as accurately as possible. The vulnerability module quantifies the physical impact of the earthquake hazard on the property at risk. Finally, the loss module
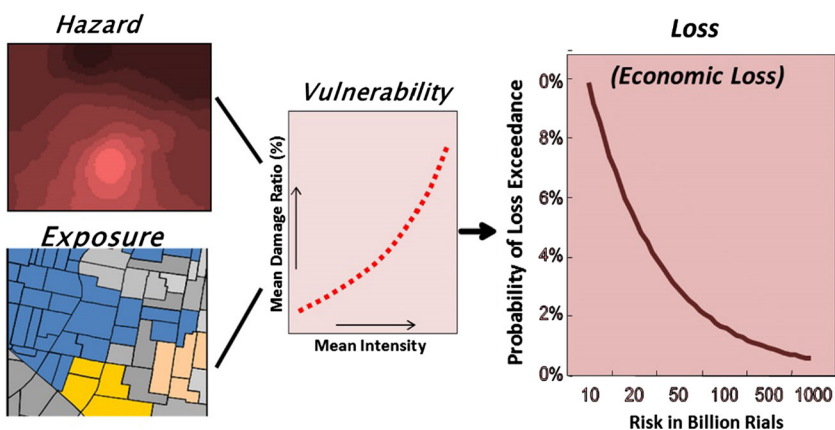

Fig. 1 Earthquake risk modeling and analysis procedure (Ghafory-Ashtiany 2010)

calculates the cost to repair and/or replace a structure (see for a detailed discussion Grossi and Kunreuther 2005 and Michel-Kerjan et al. 2012). The overall expected loss for the entire set of events, denoted as the average annual loss (AAL), is the sum of the expected losses of each individual event for a given year from exceedance probability (EP) distribution (see Grossi and Kunreuther 2005).

The results above form the basis for the probabilistic CBA. CBA is a way of making decisions for households and government based upon the probable outcomes of various mitigation actions. CBA of risks from earthquakes and potential benefits of mitigation may prompt households to reduce these risks through mitigation measures. In other words, CBA is a systematic procedure for evaluating decisions that have an impact on society (Smyth et al. 2004). There are four major steps in the CBA procedure as shown in Fig. 2. In order to analyze cost-benefits, two approaches have been considered here: structural CBA without value of statistical life (VSL) and structural CBA with VSL.

For better reading, each step within the earthquake risk model (Fig. 1) as well as CBA (Fig. 2) will be explained in the separated result sections below.

3 Earthquake risk modeling

The four major modules in earthquake risk modeling, mentioned previously, are described next.

3.1 Hazard module

The methodology of probabilistic seismic hazard analysis (PSHA) is used for preparing the probabilistic seismic hazard curve for Shiraz (district one). PSHA is a technique developed in order to set ground motion levels corresponding to certain probabilities of occurrence. In PSHA, the uncertainty of occurrence of earthquakes and the level of ground motion is explicitly considered (Fujiwara and Morikawa 2012). In order to define the earthquake hazard, the study which has been done by Sadeghi et al. (2014) is used. In the aforementioned study, Iran's active faults which are mapped based on Hessami et al. (2003) are considered first. Figure 1 in the Supplementary shows active faults that have been defined within a radius of 200 km from the center of district one including ten line sources (labeled LS) and four area sources (labeled AS). The Gutenberg–Richter formula that shows the relationship between the number of earthquakes and their magnitude has been used for each source afterward. Regarding suggested parameters for Middle-East regions, three empirical attenuation relations from Ambraseys et al. (2005), Boore et al. (1993) and Ghodrati Amiri et al. (2007) have been used for strong ground motion evaluation (see also Douglas 2006).
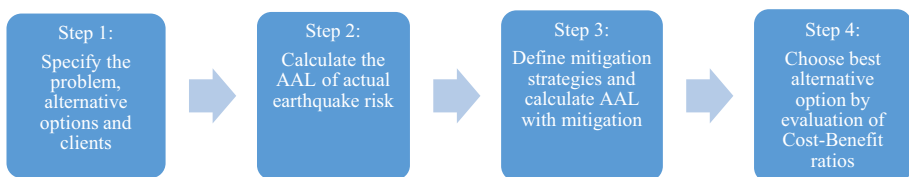

Fig. 2 Simplified benefit-cost analysis procedure

Initially, earthquake catalogs of instrumentally recorded earthquakes of the Shiraz region were prepared beginning of July 1925 to May 2013 with earthquake magnitudes starting from 4.5 to 6.5 (IIEES 2013). With the combination of all faults, seismic hazard curve has been developed for district one of Shiraz as shown in Fig. 3. Referring to the hazard curve, peak ground acceleration (PGA) for the annual exceedance probability of 10 and 2 % in 50 years are 0.37 and 0.55 g, respectively. It is notable that 10 and 2 % exceedance probabilities relate to earthquakes with 475 and 2475 return periods, respectively.

3.2 Exposure module

In the exposure module, the inventory at risk is modeled by performing a building taxonomy. A building taxonomy describes characteristics of an individual building or a class of buildings with similar characteristics. In order to do a building taxonomy, GIS-based data from Shiraz municipality were needed and had to be analyzed first (the building taxonomies are presented in the Supplementary Figure 2). In more detail, buildings have been classified by structural types into four main groups of steel, concrete, masonry and adobe. Steel buildings include different steel frames, such as moment, braced, light and unreinforced masonry infill walls. Concrete buildings are similar to steel frame buildings except that the frames are reinforced concrete. The concrete-frame buildings include concrete moment, shear walls and unreinforced masonry infill walls. Masonry buildings have perimeter bearing walls of brick, stone or concrete block with steel frame. Adobe buildings have no frame and constructed of clay or soil. Shiraz's building typologies are described in Table 2.

Based on the various editions of Iranian seismic codes, two time periods for building's construction quality have been considered, before and after 1992 known as a lower and higher quality, respectively. Regarding to these classifications, eight classes are identified. Figure 3 in the Supplementary shows the distribution of building types, and Figure 4 a, 3D view of distribution of buildings in district 1.
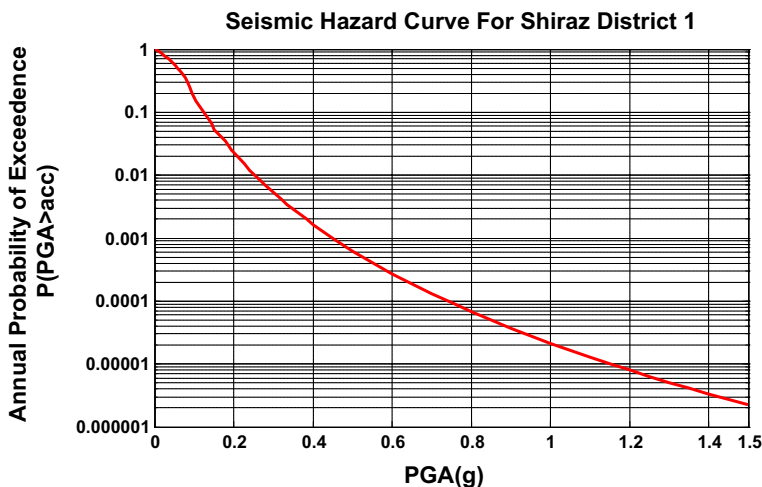

Fig. 3 Seismic hazard curve for district 1 of Shiraz. *Source*: Own calculations

3.3 Vulnerability module

The vulnerability component deals with the hazard potential to damage structures and their contents. It estimates the probability that building damage would exceed various levels as a result of ground motion (Field et al. 2012). For many types of structures, damageability may be defined in terms of fragility, defined as the probability that some limit states are exceeded, conditioned on an input level of demand. The graph of this relationship is represented as fragility functions. Unfortunately, there are no classified fragility functions for Iranian buildings available. However, due to the similarity of Shiraz to Tehran's buildings, vulnerability curves developed by the Centre for Earthquake and Environmental Studies of Tehran and the Japan International Cooperation Agency (JICA 2000) have been selected here. JICA vulnerability curves are developed based on the data collected before the year 2000 in the form of Tehran city blocks and by shifting the ATC-13 vulnerability curves through analog the intensity axis (JICA 2000 and ATC-13 1985). Figure 4 shows vulnerability functions reported by JICA 2000 for eight building categories.

It should be noted that many other fragility functions could be used. However, after testing of HAZUS and ATC-13-related curves, it was found that they are performing inconsistent with Iranian buildings and therefore are omitted in the subsequent analysis.

3.4 Loss module

The loss calculation module links the ground motion, exposure, vulnerability modules and calculates the probability of having structural losses in monetary terms. Structural loss is defined here as repair and/or replacement cost of a structure. Regarding the importance of the assessment of human losses in earthquakes, the effects of different financial mitigation strategies on human losses are investigated by considering suggested parameters given by Mansouri and Amini-Hosseini (2012) for two different occupancies. In more detail, they investigated the residential occupancy rate for a 24-h period for a normal working day in large cities in Iran in order to have a better estimation of the human casualties in earthquakes. The night and day time occupancy rates for residential buildings are presented in Table 3.

There are also some previous studies available which focused on human loss calculations in more detail, including Murakami (1992) which introduced a simulation model for calculating human losses for occupants of collapsed building due to an earthquake.

Table 2 Shiraz building typology

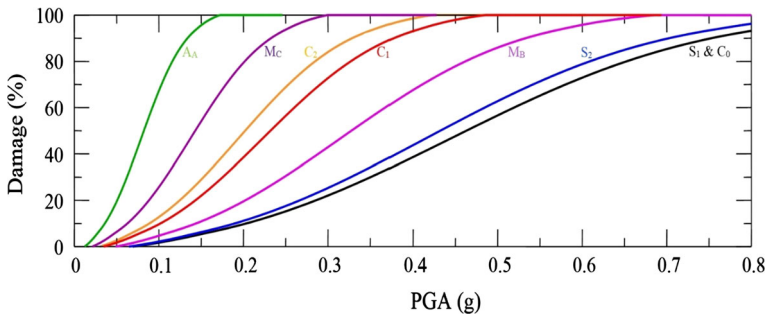| Type of structure	Year of construction	Number of stories	Label
Steel	After 1992	Below 3	S_1
	Before 1992	Above 4	S_2
Concrete	All	Above 6	C_0
	After 1992	Below 2	C_1
	Before 1992	Between 3 and 5	C_2
Masonry (brick and steel or stone structure)	All	All	M_B
Masonry (concrete block)	All	All	M_C
Adobe	All	All	A_A

Fig. 4 JICA vulnerability functions (JICA 2000)

Another example is Coburn and Spence (2002) which defined the lethality ratios for each building class corresponding to the set of parameters defining the expected proportions of occupants who are trapped, trapped who are subsequently rescued and the injury distribution in each group. More recently, Erdik et al. (2008) developed a methodology for real-time estimation of losses after a major earthquake in the Euro-Mediterranean region and also took human losses into consideration. We refer to Spence et al. (2011) for a general discussion on this issue.

Some additional important assumptions regarding structural loss estimation have to be made and are discussed next. Mitigation measures can change the structural vulnerability functions of lower quality to higher quality for selected typologies. The cost of mitigation measures is assumed to be 30 % of reconstruction cost. Another assumption is that loss calculations are performed under the Iranian official dollar exchange rate of 2013 (Central Bank of Iran 2013). Structural and human losses are then calculated using Eqs. 1 and 2, respectively, as follows (see also HAZUS-FEMA Technical Manual 2003):

$$SL = \sum_{i=1}^{8}\{D_i \times A_i \times F_i \times C_i\} \tag{1}$$

$$HL = \sum_{i=1}^{8}\{D_i \times N_i \times AP_i \times O_i\} \tag{2}$$

where SL and HL are total structural and human losses for the eight types of buildings, respectively. The total loss in each building type can be considered as a summation of the HL and SL. D_i is the structural damage for building type i. A_i is the floor area of building type i. F_i is the number of stories of building type i. C_i is the reconstruction cost of building type i. N_i is the number of examined building of building type i. AP_i is the average number

Table 3 Occupancy rate for night and daytime of residential buildings (Mansouri and Amini-Hosseini 2012)

Event	Time of the day	Occupancy ratio
Night time scenario (averaged over the time interval)	20:30–5:30	0.93
Day time scenario (averaged over the time interval)	6:30–19:30	0.55

of people living in each building of type i. Finally, O_i is the occupancy rate of death upon collapse in building type i (see Pomonis and Gaspari 2013).

Via the development of an event loss table and combining information on frequency and severity of losses, the probabilistic catastrophe model generates the distribution of the expected losses associated with all possible scenarios of earthquake events. Regarding the hazard curve, losses related to each event have been calculated by annual probability of occurrence P_j and its related losses L_j. The expected loss for a given event and the AAL can be calculated as:

$$E[L] = P_j L_j \tag{3}$$

$$AAL = \sum_{j=1}^{n} P_j L_j \tag{4}$$

The exceedance probability (EP) curve is derived for buildings before and after taking mitigation measures. Regarding Eq. 4, the area under the EP curve can be considered as the AAL. Structural mitigation measures typically decrease the vulnerability of the building and therefore reduce the expected loss. Exceedance probability curves for all types of buildings are depicted in Fig. 5

Distribution of building types and EP curves are showing that S_2 and M_B have the largest share of population in district one (see Figure 3 in the Supplementary) and have low level of losses compared to the other groups of buildings. Selected EP curves for structural and human losses in two conditions, before and after mitigation, are presented in Figs 5 and 6 in the Supplementary. In order to visualize the results, damage related to each parcel is shown in Fig. 6 for 10 % probability of occurrence in 50 years (Fig. 7 in the Supplementary shows damages related to a 2 % probability of occurrence in 50 years).

Summarizing this section, the current study examined buildings in district one of Shiraz and estimated the risk of damage due to earthquake events using a catastrophe modeling
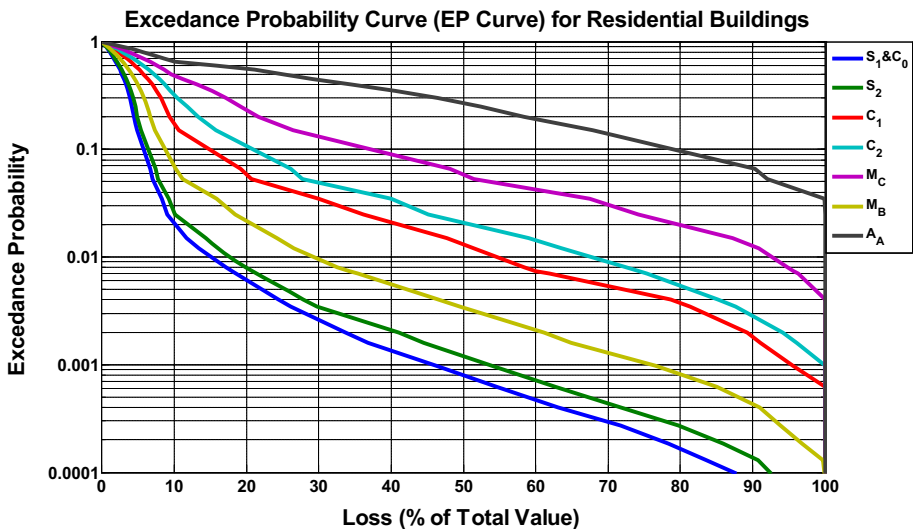

Fig. 5 Exceedance probability curve (EP) for residential building. *Source*: Own Calculations

approach which was based on a probabilistic seismic hazard analysis. The results are now used for the CBA analysis and will be discussed next.

4 Probabilistic cost-benefit analysis (CBA)

We focus on five different retrofitting loans offered by the government, banks or financial institutions perform mitigation measures for each household and use them for calculating corresponding CBA ratios. They were chosen based on suggestions from respective stakeholders as plausible scenarios, but can be also seen as a kind of sensitivity analysis (Michel-Kerjan et al. 2012). The options are based on the amount of costs for each of them. Payback of loans is assumed to be happening within 15 years, which is standardly offered in Iran (Table 4).

Using the AAL and the estimates in AAL reduction, resulting from each mitigation strategy and annual expense in regard to the five loan options, the cost-benefit ratios can be calculated based on Eq. 5.

$$\text{BC ratio} = \frac{\left(\text{AAL}_{\text{Beforemitigation}} - \text{AAL}_{\text{Aftermitigation}}\right)}{\text{Annual expense}} \tag{5}$$

The annual expenses include the costs of upgrading the structures and average annual losses which are calculated as the expected loss for the given portfolio. Total average annualized costs are the summation of the annual loan payback and AAL. By taking no action (option one), the owner would have no out-of-pocket expense, but would have a relatively high risk of sustaining large losses in 1 year. By upgrading buildings (options two, three, four and five), the owner would decrease risk and therefore relatively small losses in cases of earthquake events would occur and would need to be absorbed. For instance, Table 5 shows that none of the options are justifiable for the S_2 buildings because the annual households' expense would be more than option one (no action). For the households living in C_1 buildings taking no action (option one) cost \$2714 as an annual
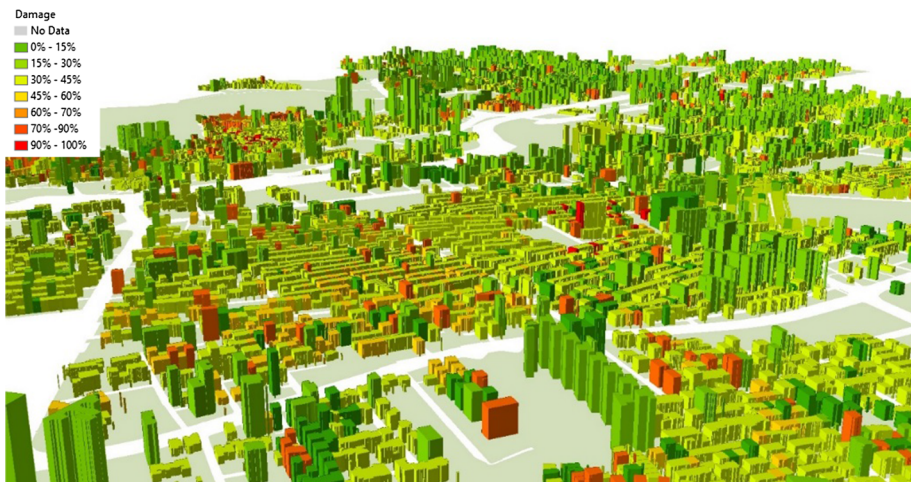

Fig. 6 3D building damage map for occurrence probability of 10 % in 50 years
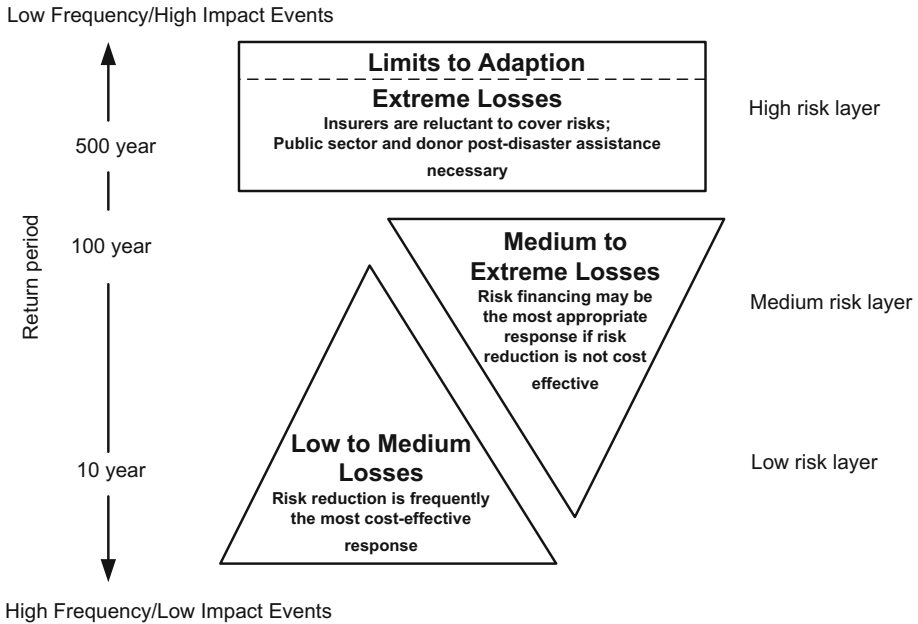
Low Frequency/High Impact Events

Fig. 7 Risk-layer approach for managing extremes (*Source*: Linnerooth-Bayer and Hochrainer-Stigler 2014)

Table 4 Different retrofitting loans for households

Options	Conditions of retrofitting loans
1 (No action)	–
2	4 % interest rate over 15 years
3	10 % interest rate over 15 years
4	15 % interest rate over 15 years
5	20 % interest rate over 15 years

loss, but if they want to mitigate their houses with option two, it can decrease their annual loss to $1112 and annual expense (came from annual loan payback) to $889. Therefore, the total annualized cost is 2001 which is less than option one ($2714). This explanation is justifiable for option three and four as well, but it has no justification for option five. For the C_2 and M_C buildings, all options are economically beneficial. Table 6 summarizes cost-benefit ratios for different retrofitting loans (described as options two, three, four and five in Table 4).

Up to now, the value of life was not considered. CBA of structures that save at-risk lives generally make use of a value of statistical life (VSL) to estimate the additional benefits (Viscusi 1993; Hochrainer-Stigler et al. 2011). For decision makers, especially the public sector, human losses are a key parameter within their decision process. However, in order to combine structural cost-benefit ratios with VSL, some important assumptions have to be made, which are discussed next: First, it is assumed that the average living area for each household is around 100 m². Secondly, in correspondence to the average number of people living in each family in Shiraz (district one), it was chosen that the average number of

Table 5 Summarizes average annualized losses and costs for different financial mitigation options for three types of buildings

Structural types	Label	Options	Annual expense ($)	Average annualized loss (AAL) ($)	Total average annualized cost ($)
Steel	S_2	1 (No action)	0	1,625	1,625
		2	1,167	1,459	2,626
		3	1,613		3,072
		4	2,007		3,466
		5	2,406		3,865
Concrete	C_1	1 (No action)	0	2,714	2,714
		2	889	1,112	**2,001**
		3	1,230		**2,342**
		4	1,530		**2,642**
		5	1,834		2,946
	C_2	1 (No action)	0	3,931	3,931
		2	994	1,243	**2,237**
		3	1,374		**2,617**
		4	1,709		**2,952**
		5	2,049		**3,292**
Masonry	M_C	1 (No action)	0	5,216	5,216
		2	848	1,670	**2,518**
		3	1,172		**2,842**
		4	1,458		**3,128**
		5	1,747		**3,417**

Numbers corresponding to the justifiable options in bold

Table 6 Summary of structural cost-benefit ratios without considering VSL

Structural type	Label	Percentage of total floor area	Cost-benefit ratios			
			Options			
			2	3	4	5
Steel	S_2	36.0	0.14	0.10	0.08	0.07
Concrete	C_1	7.1	**1.80**	**1.30**	**1.05**	0.87
	C_2	6.5	**2.70**	**1.96**	**1.57**	**1.31**
Masonry	M_C	0.02	**4.18**	**3.02**	**2.43**	**2.02**

Numbers above 1 in bold

household members is 3.41 (Iranian Census Center 2013). Thirdly, for sensitivity analysis and the importance when an earthquake actually happens, we consider events occurring during the day or during the night (Table 3).

It should be noted that including lives within a CBA can be controversial since it is ethically difficult to put a price tag on lives (Hochrainer-Stigler et al. 2011). Nevertheless, it is useful information if it is just taken as an additional information rather than standing alone for the decision maker. We include some kind of sensitivity analysis using upper and lower

Table 7 Summary of cost-benefit ratios with upper bound of VSL2 = $1,400,000 for residential buildings

Structural type	Label	Cost-benefit ratios, VSL2 = $1,400,000	
		Options 5	
		Day	Night
Steel	S_2	4.0	6.8
Concrete	C_1	67.7	113
	C_2	91.1	153
Masonry	M_C	165	227.7

values for the statistical life estimates to see possible ranges in the benefits and look just at option five, which has been defined previously and is considered as the most expensive loan option. One standard approach of VSL treats the ratio of the VSL to per capita income as constant across countries and uses estimates of the VSL from high-income countries to estimate the VSL in middle- and low-income countries. Here, a VSL calculation method suggested by Cropper and Sahin (2009), which scales the VSL, in this case for Iran, according to the country's per capita income relative to USA has been selected. The VSL in Iran, measured in US dollars, equals the VSL in the USA, multiplied by the ratio of per capita income in Iran (Y_{Iran}) to per capita income in the USA (Y_{USA}), as shown in Eq. 6.

$$VSL_{Iran} = VSL_{USA} \times (Y_{Iran}/Y_{USA}) \qquad (6)$$

This method yields for Iran, as an upper-middle-income country, VSL approximately between $730,000 (VSL1) and $1.4 million (VSL2) as lower and upper bounds, respectively. Table 7 shows now the cost-benefit ratios with upper bounds of value of statistical life for residential buildings (see Supplementary Table 1 for the lower bound results and Figure 8 for the comparison of CB ratios of day and night mode for VSL1 and VSL2).

For comparison reasons, we look back at Table 6 which shows that structural CB ratios without considering VSL has no economic justification to take mitigation actions in case of S_2 buildings. However, it also can be seen from Table 7 and Supplementary Table 1 that if each household living in the aforementioned building classes takes option five as investment of 1$ for upgrading their houses, they have a return of 2.1$ and 4$ in the case of considering VSL1 and VSL2, respectively, in day mode. These values increase for night mode to 3.6$ and 6.8$ in the case of considering VSL1 and VSL2, respectively.

The results for the other options show that considering VSL in cost-benefit analysis can significantly increase benefits of taking mitigations and save human lives and also reduce economic losses. This has important implications for the government decision-making process as well, as for some structures it would be very cost efficient to decrease human casualties as well as decrease economic losses, which could be done via some building code enforcements as well as granting subsidies for upgrading buildings. One special focus, however, may have to be put on very poor communities where some assistance would be needed to build such kind of safety nets.

5 Discussion

Iran is a very earthquake-prone country, and risk management is seen as one key element to decrease current and future human and economic losses. The need to proactively engage in developing appropriate instruments is now widely accepted as very important for

tackling emerging risks and for resilient development. In Iran, one prime focus is on structural mitigation measures which should reduce economic as well as human losses for today and in the future. However, the costs and benefits of various options are difficult to be assessed and usually done without considering both human and economic aspects. This paper filled part of this gap and performs an in-depth earthquake risk analysis for Shiraz city, in Iran. Effects of different mitigation measures on human and economic losses for buildings and corresponding changes in risk levels have been investigated. This was based on advanced catastrophe modeling approaches as well as probabilistic cost-benefit analyses.

We showed that considering the value of statistical life in cost-benefit analysis can significantly increase the structural cost-benefit ratios. This has important implications for the decision support as well as policy making side for Iran. For example, the exceedance probability curves related to the situation before mitigation (see Figures 5 to 6 in the supplementary section) showed that for concrete C_2 buildings, structural loss is about \$310 million and human loss are around 8500 fatalities. After taking mitigation actions, structural and human loss decrease to \$90 million and 2800 fatalities, respectively. Additionally, CB rations with the value of a statistical life for steel residential, S_2 buildings, which have the largest population among all buildings in district 1, showed that human losses increase cost-benefit ratios (in all mitigation options) significantly more than structural cost-benefit ratios. CB ratios without considering VSL also show that in the other types of studied buildings such as C_1, C_2 and M_C, it is cost efficient to take mitigation measure. However, if government, banks or financial institutions only offer loans with lower interest rates for mitigation payback, there may be an economic justification for these households to take mitigation actions for most of building classes too. On the other hand, by considering the human losses which are a key parameter for the government and the society as a whole, mitigation actions would be essential.

It should be noted that the investigation in structural mitigation measures, while an essential first step, is only a part of the full picture. At some point, structural mitigation is simply too costly as well as not efficient anymore to decrease risks. Hence, other financial-related measures should come into play. Recently, within the climate disaster-related field, a risk-layer approach is suggested which separates the risk into different layers (Fig. 7).

For our case study, we addressed the low and medium risk layer, and in future research, the extreme risk layer has to be analyzed too. As the loss exceedance functions are now estimated, this can be performed in a very flexible manner, e.g., incorporating the financial resources for each household to determine their coping capacities and therefore also the risks which need to be hedged. Notice, for very extreme losses, there may be no options available (or available but too costly) and post disaster assistance would be necessary. Last but not least, due to changes in the risk, e.g., increases in exposure rates as well as vulnerability, there may also be a limit to adaptation assumed. Moreover, the mutual benefits of structural mitigation and financial risk management should not be underestimated and it may very be the case that both together are needed for a successful sustainable risk management strategy. Further research in this area is currently underway.

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