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An Optimization Model for Financial Resource Allocation Towards Seismic Risk Reduction

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Abstract

This paper presents a study on determining the degree of effectiveness of earthquake risk mitigation measures and how to prioritize such efforts in developing countries. In this paper a model is proposed for optimizing funds allocation towards risk reduction measures (building retrofitting) and reconstruction process after potential earthquakes in a regional level. The proposed model seeks optimized strategy towards risk reduction based on minimizing or maximizing various criteria such as retrofitting costs, economic damages including business interruption losses, number of human casualties and other seismic hazard consequences. The main objective of this model is to find optimum strategy for maximizing the benefits of available economic resources for retrofitting and reconstructions. Regional seismic hazard and building stocks and their vulnerability functions are used to model probabilistic seismic risk for a given region. The proposed model is adjusted for developing countries exposed to high seismic sources like Iran. In order to present the application of the proposed method, the approach is applied for a pilot area in Tehran. Results illustrate the variation of mitigation in particular, structural retrofitting expenditures and reconstruction expenditures by structural type for buildings in this region. In addition, recommended expenditures by year for the case study are obtained according to the results.

Key Words: Optimization, Vulnerability, Reconstruction, Earthquake Risk Mitigation

1. Introduction

Natural catastrophes threat human lives and properties, resulting in wide spread social and economic disruptions. From economic loss point of view, natural hazards have resulted in significant losses in developed countries in the recent years; examples are the Kobe earthquake and Hurricane Katrina. However, the social impact of natural catastrophe has proven to be of more devastating magnitude in the developing countries as shown by recent events in India, Iran and China. Besides, economic losses in the developing countries, although much lower than the developed counties, are still of significant importance compare to national GDP. Such losses include damages to normal property and infrastructure, business interruption and macro-economic effects following big natural catastrophes. Natural catastrophe risk management measures in recent years have addressed ways to reduce the adverse effects of natural catastrophes. Such measures include improving design codes, buildings and infrastructures retrofitting, raising public awareness, early warning systems and risk transfer systems. Usually a large and diverse group of stakeholders are involved in risk mitigation plans, each with different, sometimes competing objectives, constraints, and available strategies. This causes the decision making process on the risk mitigation measures to be even more complicated. Even focusing on structural upgrades as a mitigation measure, one would still have to decide which of thousands of structures to upgrade, how, and when. The problem dimensions expand further because of various types of impacts an earthquake may have, including for example, deaths, injuries, structural damage, business interruption, environmental damage, and other social and economic consequences. Moreover, impacts across a region are spatially correlated, which should be considered because it affects the variability of total regional losses. The earthquake risk mitigation decision problem in any level is also highly uncertain and dynamic. There is substantial variability in possible mitigation investment outcomes due to the large uncertainty in earthquake occurrence. Because the return periods of damaging earthquakes are generally tens to hundreds of years, a long time horizon is required for

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analysis. Finally, an appropriate mitigation plan depends on the character of risk in the specific region of interest and what would driving such risks (e.g., frequent earthquakes, vulnerable structures) and what is controllable. Each mitigation strategy targets a different aspect(s) of risk, so the best combination of efforts will be tailored towards the issues particular to the region [1].
Concerns have always been expressed regarding the distribution of financial funds irrespective of the magnitude of risks and risk reduction opportunities within a region and across different regions. Therefore funds and national investments are not utilized efficiently and a lot of opportunities are lost. For these reasons, from the first day when risk management and mitigation plans were proposed and implemented, different methods were also proposed and introduced to estimate and assess the effectiveness and profitability of these plans and also to compare the outcomes of their probable implementation. The methods which are proposed for assessing the effectiveness and profitability of risk mitigation plans have been improved over time and they can now be used for assessing optimum measures. Defining optimum plans mostly depends on investment, investor and the stakeholder or institution which invests for risk reduction plans. Objectives, constraints, and available strategies of stakeholder can have the main role in defining optimum. Most of the previous studies have compared a small number of predefined mitigation alternatives to choose the single best alternative. There have been a few studies using optimization modeling approach in which one can choose the set of mitigation alternatives that maximize expected specified objective subject to a limited budget or other constraints. Such methods can also help decision makers to allocate their financial resources to more beneficial measures or to distribute budget across number of measures to optimize the benefits or minimize the considerable risks. Dodo *et al.* [2] summarize previous researches related to resource allocation for natural disaster risk management by grouping them into four main approaches. These methods are:

1. Deterministic Net Present Value (NPV) Analysis
2. Stochastic NPV Analysis
3. Multi-Attribute Utility Models
4. Optimization Models

Dodo et al. [2] developed a linear program to support regional earthquake mitigation resource allocation and illustrated its use through a small case study in Los Angeles County using optimization model. The model determined with buildings - by structural type, occupancy type, and census tract location - should be upgraded so as to minimize total mitigation and expected post-earthquake reconstruction expenditures. Dodo et al. [3] presented two efficient solution algorithms to solve the model for a realistic application area. Davidson et al. [4] extended this model to include the objective of ensuring equity among various groups of people in earthquake risk management. Vaziri [1] modified the Dodo et al. [2] optimization modeling approach, so it can be applied in a highly seismically active developing country like Iran, India and Turkey. In such countries economic resources may be more constrained, damage more widespread, and death tolls much higher than in the US and Japan. First, the model recognizes the likely possibility that limited economic resources will be available for post-earthquake reconstruction by incorporating budget limits, and although it is treated as a less desirable alternative, if economically necessary, allowing the possibility that some damaged buildings will not be reconstructed immediately. The model keeps track of damaged buildings and let them rebuild later when more funds are available. Second, the new model expands the set of possible mitigation alternatives to allow not just upgrading of a particular structural type, but a change in structural type as well. Third, since a sound development plan ideally uses post-disaster reconstruction as an opportunity to introduce safer conditions, the model relaxes the assumption that all buildings should be reconstructed to their pre-earthquake condition, instead allowing damaged buildings to be reconstructed to any specified seismic design level and structural type. It also allows the decision maker to restrict mitigation and reconstruction decisions in particular cases, for example, a certain design level or structural type is no longer allowed by the current building code. Finally, because death tolls may be very high in developing countries like Iran, the model includes as one objective minimizing the chance of an extremely high death toll in any one earthquake (as well as minimizing the average annual death toll across earthquakes)[1]. The model addresses three main questions:
(1) How much should be spent on pre-earthquake mitigation that aims to reduce future losses, versus payment for post-event damages?
(2) Which buildings should be mitigated and how?
(3) Which buildings should be reconstructed and how?

2. Modelling approach

This paper follows the optimization modeling approach used by Vaziri [1] with modifications taking into account Business Interruption losses (BI) are based on building damage state and occupancy type. Buildings are grouped into categories based on their locations, structural types (e.g. masonry, steel), occupancy types (e.g. residential, hospital), and seismic design levels (e.g. to a specific code standard). A mitigation alternative is defined as upgrading a given building floor area (m^2) of a particular structural and occupancy type in a specified location either from one seismic design level to another, or from one structural type to a more seismically resistant type. Census block units are used as location unit for analysis. At each time period, decisions are first made on the selection of buildings to be mitigated and how (Fig. 1). Those decisions are performed and then the expected annual damage happens, calculated as the product of the expected damage including BI given an earthquake and its hazard-consistent occurrence probability, summed over all possible earthquakes The probability that a building of a given type enters a damage state after an earthquake is a function of the ground shaking at the site and building vulnerability. Since multiple damage states are possible in reality, given the precision of available data, multiple damage states are considered here. Since there may be insufficient resources to repair all the damages immediately, it is possible that to repair a damaged building to a specified structural type and design level or to leave it unrepaired, thus losing the floor area from the building inventory. The model keeps track of the cumulative floor area that is not reconstructed. This record of cumulative lost building inventory is updated after all reconstruction decisions are made. Based on the time required for building reconstruction and also the number of unrepaired buildings, business interruption losses are also estimated. Finally, the state of the building inventory is updated for use in the beginning of the next time period.

In this model, we represent seismic hazard using the hazard-consistent probabilistic scenario method [5], in which a relatively small set of all possible earthquake scenarios are selected and their annual occurrence probabilities are adjusted so that at each block the hazard curve developed based on the hazard-consistent scenarios matches that determined by a full PSHA (or Monte Carlo simulation) as closely as possible [5]. This method provides a set of scenarios that are small enough to be computationally feasible for optimization process while representing the full distribution of annual loss and capturing spatial correlation better than PSHA [5]. For each earthquake, PGA's are calculated for each building block using attenuation relationship. This model deals with direct losses related to structural damage and deaths as well as indirect business losses. It also focuses on structural upgrading and replacement as mitigation alternatives. Benefits and costs unrelated to earthquake risk are not considered. Table 1 summarizes the list of required input data and their sources. It may be difficult to define ''correct'' values for the user-defined parameters; sensitivity analyses over a range of values will likely provide more insight.

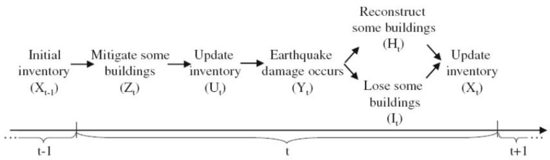

Fig. 1. Evolution of building inventory in time period t, with model floor area variables[1]

Table 1. required input and where it came from for the case study

Variable	Description	Source
X^{c}_{ijk0}	Inventory of buildings of structural type *i*, and occupancy type *j*, are in block *k*, and seismic design level *c* at time 0	Data from municipality 2005 and 2007
P	Initial population	Data from 2007
R^{cd}_{ijk}	Reconstruction cost per unit area of structural type *i*, and occupancy type *j*, are in block *k*, and seismic design level *c* with damage state *d*	Estimated by authors Based on statistic dada
$F^{i'c'}_{ijkc}$	Unit cost of mitigating a building of structural type *i*, class *m*, and seismic design level *c* to structural type *i'* and seismic design level *c'*	Estimated by authors Based on statistic dada
a^{cld}_{ijk}	Proportion of buildings of structural type *i*, and occupancy type *j*, are in block *k*, and seismic design level *c* that is expected to damage state *d* in earthquake *l*	JICA [6] and HAZUS [7] curves
P^{l}	Per-period hazard-consistent occurrence probability of earthquake scenario *l*	Hazard analysis
V^{cd}_{ijkt}	Per unit floor area cost of not reconstructing buildings of structural type *i*, and occupancy type *j*, are in block *k*, and seismic design level *c* with damage state *d* at the end of time period *t*	Estimated by authors c
L^{cd}_{ijk}	Expected number of deaths if a unit of floor area of building of structural type *i*, and occupancy type *j*, are in block *k*, and seismic design level *c* collapses	Applied JICA (2000) method [6]
$OO_j\,\%$	percent owner occupied for occupancy j	HAZUS table[7]
DC_j	disruption costs for occupancy j ($\$/m^2$)	HAZUS table[7]
t_{jd} , T_{jd}	recovery time for damage state d and occupancy j in Not reconstructed buildings and reconstructed buildings respectively.	HAZUS table[7]
LOF_{jd}	loss of function time for damage state d and occupancy j	HAZUS table[7]
RF_j	recapture factor for occupancy j	HAZUS table[7]
INC_j	income per day (per square meter) for occupancy class j	User-defined Based on Iran census data from census center of Iran
$\mathrm{Re}nt_j$	rental cost ($\$/m^2$/day) for occupancy j	Iran census data from census center of Iran
μ	Penalty term in the objective function for solutions with an extremely large death toll	User-defined
κ	Percentage of the population that defines an extremely large death toll	User-defined
α	Monetary value of a lost life	User-defined
B_t	Available budget in period *t*	User-defined Based on Iran census data from census center of Iran
D_Z,D_H,S_n, Δ_Z,Δ_H	Sets of prohibited structural types and design levels, and building type subsets	User-defined

The final model is a linear equation with the objective and the constraints. Assuming that mitigation is only to an improved seismic design code ($c' > c$), the mitigation decisions are represented by:

$$U_{ijkt}^{c} = X_{ijk,t-1}^{c} + \sum_{i'}\sum_{c'} Z_{i'jkc't}^{ic} - \sum_{i}\sum_{c} Z_{ijkct}^{i'c'} \quad \forall i,j,k,c,t \quad (1)$$

In which $X_{ijk,t-1}^{c}$ represents the floor area *(m^2)* of building with structural type *i* and occupancy type *j*, designed to seismic design level *c*, in block *k* and at the end of time period *t – 1*. $Z_{ijkct}^{i'c'}$ represents the floor area of buildings *(m^2)* which are mitigated to structural type *i′* and seismic design level *c′* during time period *t*. Thus, $X_{ijk,t-1}^{c}$ and U_{ijkt}^{c} describe the inventory at the beginning of the time step and after mitigation decisions have been implemented, respectively (Fig.1). The second term on the right side represents all floor area that began the time step with structural type *i′* and seismic design level *c′* and was mitigated during the time step to structural type *i* and seismic design level *c*. Similarly, the third term on the right side represents all floor area that began the time step as structural type *i* and seismic design level *c* and was mitigated to some other structural type *i′* and seismic design level *c′*. Additional constraints are considered in the mitigation decisions through eqs. 1-5. First, a building cannot be mitigated to the same or a lower seismic design level. Second, buildings may not be mitigated to any structural type in a set Δ_Z of seismically undesirable structural types (e.g., adobe), or in a set D_Z of undesirable design levels. Third, if the building inventory is partitioned into *N* mutually exclusive building type subsets [S_n, where $n \in (1,\ldots, N)$], then change in structural type as a mitigation choice can be implemented between buildings within set S_n only. For example, if the subsets are low-rise and high-rise buildings as in the case study, then one could mitigate a low-rise building by replacing it with another low-rise structural type, but not a high-rise one.

$$Z_{ijkct}^{i'c'} = 0 \quad \forall j,k,t,i,i',c > c' \ (2)$$

$$Z_{ijkct}^{i'c'} = 0 \quad \forall j,k,t,c,c',i,i' \in \Delta_Z \ (3)$$

$$Z_{ijkct}^{i'c'} = 0 \quad \forall j,k,t,c,i,i',c' \in D_Z \ (4)$$

$$Z_{ijkct}^{i'c'} = 0 \quad \forall j,k,t,c,c',i \in S_n, i' \notin S_n \ (5)$$

Each earthquake (*l*) is defined by a magnitude and location with a per-period probability P_l. The set of earthquakes and the associated probabilities are assumed to be given as part of the input data. The expected floor area *(m^2)* of buildings of structural type *i*, occupancy type *j*, in block *k*, and seismic design level *c* to be damaged in damage state *d* in earthquake *l* in time *t* is (Y_{ijkt}^{cld}):

$$Y_{ijkt}^{cld} = a_{ijk}^{cld} U_{ijkt}^{c} \quad \forall i,j,k,c,t,l,d \ (6)$$

In which a_{ijk}^{cld} is the proportion of buildings that will be damaged in damage state *d* if earthquake *l* happens. A key component of the model that makes it more suitable for weaker economies or earthquakes causing more widespread damage is that it does not require the entire damaged inventory at every time period *t* to be reconstructed in the same time period. The floor area *(m^2)* of buildings with structural type *i*, occupancy type *j*, in block *k*, and seismic design level *c* that is damaged in damage state *d* and not reconstructed to any structural type by the end of time period *t (I_{ijkt}^{cd})* is:

$$I_{ijkt}^{cd} = I_{ijkt-1}^{cd} + \sum_{l} P^{l} Y_{ijkt}^{cld} - \sum_{i'}\sum_{c'} H_{ijkct}^{i'c'd} \quad \forall i,j,k,c,t,l,d \quad (7)$$

In which $H_{ijkct}^{i'c'd}$ is the floor area *(m^2)* of buildings with structural type *i*, occupancy type *j*, in block *k*, and seismic design level *c* before it was damaged in damage state *d* and reconstructed as structural type *i′* and seismic design level *c′* in time period *t*. As with mitigation decisions, some set of structural types (Δ_H) or seismic design levels (D_H) may be unacceptable reconstruction options (eqs.8,9) perhaps because new seismic codes prohibit them, and if a unit area of a damaged building is from a subset S_n, it should be rebuilt to a structural type from the same subset (eq. 10):

$$H_{ijkct}^{i'c'd} = 0 \quad \forall i,j,k,c,t,d,c',i' \in \Delta_H \ (8)$$

$$H_{ijkct}^{i'c'd} = 0 \quad \forall i,j,k,c,t,d,i',c' \in D_H \ (9)$$

$$H_{ijkct}^{i'c'd} = 0 \quad \forall j,k,c,c',t,d,i \in S_n, i' \notin S_n \ (10)$$

After the effects of mitigation, earthquake damage, and reconstruction are determined, therefore, the total floor area *(m^2)* of buildings of structural type *i*, occupancy type *j*, in block *k*, and seismic design level *c* at the end of the time period *t* is given by

$$X_{ijkt}^{c} = U_{ijkt}^{c} - \sum_{l}\sum_{d} P^{l} Y_{ijkt}^{cld} + \sum_{i'}\sum_{c'}\sum_{d} H_{i'jkc't}^{icd} \quad (11)$$
$$\forall j,k,c,t,d,i$$

The time required to reconstruct the damage building and restore occupant back to the building causes further losses described as Business Interruption (*BI*). The *BI* loss for reconstructed building during period *t* can be estimated using the following equation:

$$BILossH_{ijkt}^{cd} = \sum_{i'}\sum_{c'} H_{ijkct}^{i'c'd} (REL_{j}^{d} + YLOS_{j}^{d} + RY_{j}^{d}) \quad \forall i,j,k,c,t,l,d,i',c' \quad (12)$$

$$REL_j^d = (1 - OO\%_j) \times factor_d \times DC_j + OO\%_j \times factor_d \times (DC_j + Rent_j \times T_{jd}) \quad \forall j,d \quad (13)$$

$$YLOS_j^d = (1 - RF_j) \times LOF_{jd} \times INC_j \quad \forall j,d \quad (14)$$

$$RY_j^d = (1 - OO\%_j) \times factor_d \times Rent_j \times T_{jd}) \quad \forall j,d \quad (15)$$

In which $H_{ijkct}^{i'c'd}$ is the floor area *(m²)* of buildings before it was damaged in damage state *d* and is reconstructed as structural type *i'* and seismic design level *c'* in time period *t*. Then $\sum_{i'}\sum_{c'} H_{ijkct}^{i'c'd}$ is the floor area *(m²)* of building before it was damaged in damage state *d* and is reconstructed in time period *t*. REL_j^d, $YLOS_j^d$ and RY_j^d are the relocation costs, income losses and rental income losses for a unit of floor area *(m²)* occupancy type *j* and damage state *d,* respectively. DC_j (Rial/m²)is the disruption costs for occupancy type *j* ,T_{jd} is the recovery time for occupancy type *j* and damage state *d*. *%OO*$_j$ is the percent owner occupied for occupancy type *j,Rent*$_j$ is the rental cost (Rial/m²/day) for occupancy type *j*. $factor_d$ is equal zero for no damage or light damage states and is equal one for moderate and heavy damage states.INC_j is the income per day (per square meter) for occupancy type *j*. LOF_{jd} is theloss of function time for occupancy type *j* and damage state *d*. RF_j is the recapture factor for occupancy type *j*.

Similarly BI loss for non reconstructed building during period *t* is:

$$BILossI_{ijkt}^{cd} = I_{ijkt}^{cd}(REL_j^d + YLOS_j^d + RY_j^d) \quad \forall i,j,k,c,t,l,d \quad (16)$$

$$REL_j^d = (1 - OO\%_j) \times factor_d \times DC_j + OO\%_j \times factor_d \times (DC_j + Rent_j \times t_{jd}) \quad \forall j,d \quad (17)$$

$$YLOS_j^d = (1 - RF_j) \times t_{jd} \times INC_j \quad \forall j,d \quad (18)$$

$$RY_j^d = (1 - OO\%_j) \times factor_d \times Rent_j \times t_{jd}) \quad \forall j,d \quad (19)$$

In which I_{ijkt}^{cd} be the floor area *(m²)* of structural type *i*, occupancy type *j*, in block *k*, and seismic design level *c* before it was damaged in damage state *d* and is not reconstructed during time period *t*. It is assumed that there is a maximum budget B_t to be spent in each period *t*. *t*. Let $F_{ijkc}^{i'c'}$ be the unit cost of mitigating a building of structural type *i*, occupancy type *j*, in block *k*, and seismic design level *c* to structural type *i'* and seismic design level *c'*. Let R_{ijk}^{cd} be the unit construction cost of structural type*i*, occupancy type *j*, in block *k*, and seismic design level *c* which is damaged in damage state *d*. The decision of how to allocate the available budget between mitigation and reconstruction at every time period *t* is represented by:

$$\sum_i\sum_k\sum_j\sum_c\sum_{i'}\sum_{c'}\sum_d R_{ijk}^{cd} H_{ijkct}^{i'c'd} + \sum_i\sum_k\sum_j\sum_c\sum_{i'}\sum_{c'} F_{ijkc}^{i'c'} Z_{ijict}^{i'c'} \le B_t \quad \forall t \quad (20)$$

In practice, mitigation and reconstruction expenditures may or may not be drawn from the same budget. Conceptually, however, there is a tradeoff between spending on pre-earthquake mitigation to reduce losses and post-earthquake reconstruction to repair damage and this constraint allows the user to examine that tradeoff. If desired, one could modify the formulation by defining separate mitigation and reconstruction budgets. A final constraint represents the desire to guard against scenarios that would produce an unacceptably large number of casualties. It is assumed that we have just one causality state and it is dead. It is also assumed that just heavily damaged or collapsed building will kill people.

$$\sum_i\sum_k\sum_j\sum_c\sum_t\sum_d Y_{ijkt}^{cld} L_{ijk}^{cd} - \gamma_t^l \le \kappa P \quad (21)$$
$$\forall t,l,d = heavily\ \&\ collapse$$

where L_{ijk}^{cd} is the expected number of people killed if a unit of floor area *(m²)*of building structural type *i*, occupancy type *j*, in block *k*, and seismic design level *c* is in *d=heavily damage* or collapses. Casualties were estimated as in JICA[6], as a function of the number of collapsed buildings, number of people per building, occupancy at the time of the earthquake, percentage of occupants trapped by collapsed buildings, percentage of occupants killed immediately by building collapse, and percentage of injured that subsequently die before rescue. It was assumed that the earthquakes occur at night and no rescue is possible. Other casualty scenarios could be incorporated with no modification in the model [6]. *P* is the study region's initial population; the user-defined parameter $\kappa \in [0,1]$ defines ''large'' death toll as a percentage of the population; and γ_t^l is the number of deaths in earthquake *l* and period *t* beyond the threshold defining an unacceptably large death toll(κP). The following non-negativity requirements must also hold for the decision variables:

$$U_{ijkt}^c, X_{ijkt}^c, I_{ijkt}^{cd} \ge 0 \quad \forall i,j,k,t,c,d \quad (22)$$

$$Z_{ijkct}^{i'c'}, H_{ijkct}^{i'c'd} \ge 0 \quad \forall j,k,c,c',t,d,i,i' \quad (23)$$

$$\gamma_t^l \ge 0 \quad \forall l,t \quad (24)$$

$$Y_{ijkt}^{cld} \ge 0 \quad \forall i,j,k,c,t,d,l \quad (25)$$

$$Min\sum_{t}\left(\begin{array}{l}\sum_{i}\sum_{k}\sum_{j}\sum_{c}\sum_{i'}\sum_{c'}\sum_{d} R_{ijk}^{cd}H_{ijkct}^{i'c'd}+\sum_{i}\sum_{k}\sum_{j}\sum_{c}\sum_{i'}\sum_{c'} F_{ijkc}^{i'c'}Z_{ijict}^{i'c'}+\\ \alpha\sum_{i}\sum_{k}\sum_{j}\sum_{c}\sum_{l}\sum_{d}P^{l}Y_{ijkt}^{cld}L_{ijk}^{cd}(d=heavily\ damage)+\sum_{i}\sum_{k}\sum_{j}\sum_{c}\sum_{d}V_{ijkt}^{cd}I_{ijkt}^{cd}\\ +\mu\sum_{l}P^{l}\gamma_{t}^{l}+\sum_{i}\sum_{k}\sum_{j}\sum_{c}\sum_{d}BILossH_{ijkt}^{cd}+\sum_{i}\sum_{k}\sum_{j}\sum_{c}\sum_{d}BILossI_{ijkt}^{cd}\end{array}\right) \quad (26)$$

The objective of the model is to minimize the total mitigation cost, expected post-earthquake reconstruction cost, monetary value of the total expected loss of life, monetary value of total building inventory lost due to limited reconstruction resources, risk of a large death toll, and monetary value of the Business Interruptions loss, the terms in eq.26, respectively.

In this expression, $\alpha$is the monetary value of a lost life; V_{ijkt}^{cd} is the per-period, per-unit floor-area cost of not reconstructing buildings of structural type *i*, occupancy type *j*, in block *k*, and seismic design level *c* which is damaged in damage state *d* (i.e., losing building inventory). $\mu \geq 0$ represents a weight to characterize the relative importance of the objective of minimizing the chance of an extremely large death toll. A higher value of μrepresents more risk aversion. A life lost obviously cannot be ‘‘reconstructed’’ and we do not presume to know the value of a life. There are many ways to estimate the value of a statistical life (e.g., willingness to pay, foregone earnings). The various methods can produce very different estimates, and there are widely discussed challenges associated with each method (e.g., Graham and Vaupel1981 [8]). By including in the analysis avoided deaths and injuries as a benefit of earthquake mitigation, we simply aim to enable the model user to examine the effect of varying the assumed value of a statistical life if desired. The model results indicate how to allocate the budget among mitigation $Z_{ijkct}^{i'c'}$ and post-earthquake reconstruction alternatives $H_{ijkct}^{i'c'd}$; and how much lost building inventory I_{ijkt}^{cd}, how many deaths $Y_{ijkt}^{cld}L_{ijk}^{cd}$, and how many deaths over the ‘‘large death toll’’ threshold $P^{l}\gamma_{t}^{l}$ are expected to result.

3. Case Study

3.1. Scope

In order to present the application of the proposed method, a case study was conducted for district 3 in northern Tehran, the capital city and political and economic center of Iran, one of the most earthquake-prone countries in the world. District 3 in northern Tehran is an extension to the city, mostly developed in the last few decades. From socioeconomic point of views, the district accommodates mostly middle to high class citizens with many newly developed apartment blocks. Tehran is located at the foot of the Alborz Mountains, which form part of the Alps–Himalayan Orogenic Zone. It is a highly seismic area surrounded by many active faults. The case study focuses on the ground shaking hazard, but the analysis could be modified to include the effects of liquefaction or other collateral hazards into the model formulation. For consistency, all monetary values are presented in US dollars, using the 2005/06 IMF exchange rate of 9,026 Rials per US dollar [9].

3.2. Input data

In the case study, the time step is 1 year and the investment horizon is 10 years. The 14 earthquakes identified by Vaziri [5] were assumed to represent the regional seismicity (Fig. 2; Table 2). The 15th scenario is the no-earthquake scenario with annual probability of 0.50. In this study, building inventory for buildings in district 3 in Tehran are collected from census study and based on census zone. Tehran is divided into 3,173 census zones, 114 communes and 22 district units. For each census zone, number of buildings, sum of building areas by structural type and population count are provided. To reduce computation run time in this study, data provided on the census level are aggregated by commune units. There are 6 commune units in district 3 which the case study is performed for. Fig. 3 shows the administrative units for Tehran and district 3. Statistical data on population and building inventory are extracted from data collected in a microzoning study of the Greater Tehran Area conducted by JICA [6]. However, in the case study presented in this paper building database is categorized to 11 different structural types i (1- 11). Therefore, Table 3 is used to connect different types of buildings defined in this paper to building types defined by JICA [6] and building types defined by HAZUS[7] in order to use their fragility curves

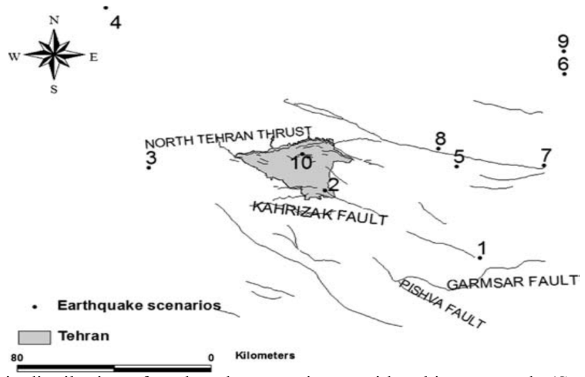

Fig. 2.Geographic distribution of earthquake scenarios considered in case study (Source: Vaziri [5])

Fig. 3. Administrative units for Tehran City, 3173 census zones, 114 commune and 22 district units, location of district city and its 6 commune unites in Tehran city.

Table 2. Hazard-consistent annual occurrence probability and magnitude of the earthquake scenarios considered in the case study (Source: Vaziri [5])

EQ ID or fault name	Magnitude	Hazard-consistent probability
1	7.1	0.05
2	7.0	0.0003
3	7.1	0.029
4	7.6	0.05
5	6.4	0.05
6	6.6	0.05
7	7.0	0.05
8	5.4	0.05
9	6.7	0.0484
10	4.1	0.0083
11 Garmsar MCE (maximum credible earthquake)	6.9	0.05
12 Kahrizak MCE	6.6	0.0037
13 North Tehran MCE	6.9	0.0057
14 Pishva MCE	6.5	0.05

To calculate a_{ijk}^{cld} values (Table 1), it is necessary to prepare loss estimation platform. The basic component of any seismic loss estimation is a representation of seismic hazard. Peak Ground Accelerations (PGAs) from all 14 earthquake scenarios for communes of district 3 are estimated here. Therefore, three attenuation relationships including Iranian (Ramazi 1999[10]), regional (Ambraseys and Bommer 1991[11]), and global (Sarma and Srbulov 1996[12]) were applied to estimate these PGAs. Seismic damage is assigned to each group of buildings based on estimated PGA and associated damage ratios from building fragility curves. 11 building taxonomies (presented in Table 3) and three damage states as slight, moderate and heavy and collapse are considered here. Fragility curves proposed by JICA [6,7] are used here. For heavy damage and collapse states, fragility curves presented by JICA [6] are used. For other two damage states HAZUS [7] fragility curves are used. JICA fragility curves are plotted in Fig. 4.

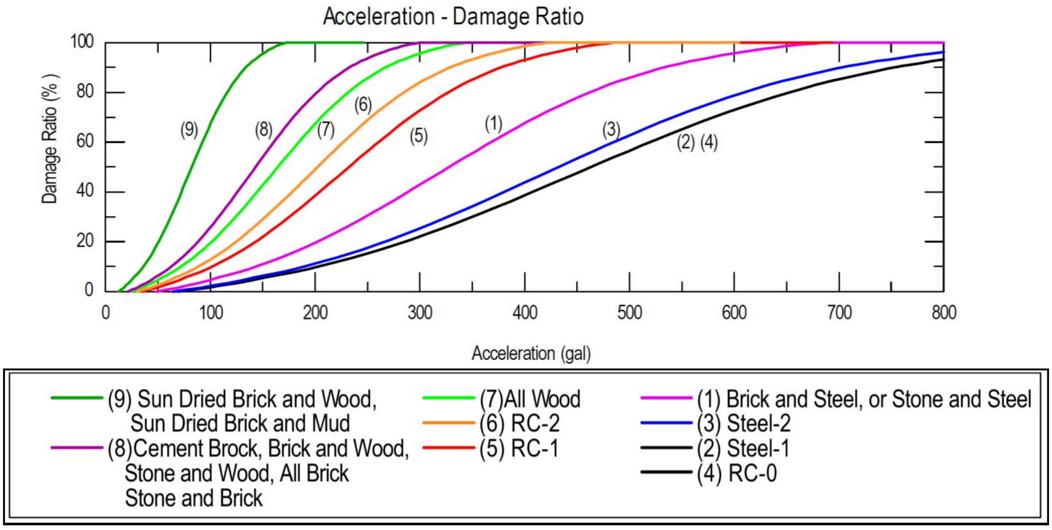

Fig. 4. Building fragility curves (damage ratio versus earthquake acceleration (1gal=0.001g) (Source: JICA [6])

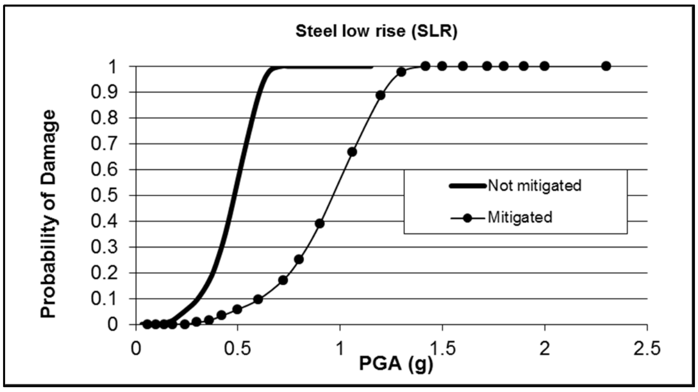

Fig. 5. Steel low rise (SLR) building fragility curve showing the damage ratio

For each structural type, three two design levels are considered, *c(1-2)*, not mitigated and mitigated. According to Vaziri et al.[1] the goal of mitigation is assumed to achieve the Life Safety Performance Level defined in retrofit guidelines in Monograph No. 360[13], which are similar to FEMA 356[14]. Based on such assumptions and knowledge of existing buildings in Tehran, the effect of mitigation is defined as a rightward shift in the fragility curve so as to double the PGA necessary to reach the same damage ratio, Fig. 5 shows fragility curves for SLR (Table 3) buildings with and without mitigation implementationversus earthquake acceleration for heavy damage and collapse states, without and with mitigation implementation [15]

The associated unit mitigation cost, $F_{ijkc}^{i'c'}$, and the unit reconstruction costs, R_{ijk}^{cd}, are estimated as shown in Table 3. It is assumed that sun dried brick (SDB) and masonry buildings (MLR and MMR) are among unacceptably weak structural types that are not appropriate for mitigation or reconstruction measures when they are under heavy damage or collapse conditions. This is also the same for all wood structural type; therefore, mitigation for such buildings means reconstruction to the new building types and also to mitigated ones in the same category. Structural types are divided into 3 categories: low-rise, mid-rise and high-rise, and it is assumed that demolishing a building from one category and reconstructing it as mitigation or reconstruction decision to a structural type from other categories is not an option. As three different damage states are considered in this case study, the reconstruction expenditures(*R* values) are presented for different damage states. Moreover, it is possible to reconstruct buildings to different types of design levels. For all buildings which are entered in slight and moderate damage states, they can be reconstructed to their primary situation. However, if All-wood, SDB, masonry buildings (MLR and MMR), and half frame buildings (HLR, HMR, HHR) damaged heavily or collapsed, they have to be reconstructed to the steel and concrete structural types. The cost of not reconstructing a building was assumed to be five times the cost of reconstructing the same building type, assuming that the functions the building served must

Table 3. Building structural type variants and the Unit Mitigation Cost (UMC) and Unit Reconstruction Cost (URC)[1,15]

Structure type	Name	Category Name in JICA for heavily damage	Structural type name in HAZUS for slight and moderate damage	Category	UMC ($) to	URC ($) for slight damage to		URC ($) for moderate damage to		URC ($) for heavily damage to	
					Mitigated	Not mitigated	Mitigated	Not mitigated	Mitigated 1	Not mitigated	Mitigated
Steel Low Rise	SLR	BT-2	Mean of S1L and S2L (pre-code)	Low	133	83	216	166	299	332	386
Steel Medium Rise	SMR	BT-3	Mean of S1M and S2M (pre-code)	Medium	122	83	205	166	288	332	386
Steel High Rise	SHR	BT-3	Mean of S1H and S2H (pre-code)	High	122	83	205	166	288	332	386
Concrete Low Rise	CLR	BT-5	Mean of C1L and C2L (pre-code)	Low	122	83	205	166	288	332	386
Concrete Medium Rise	CMR	BT-6	Mean of C1M and C2M (pre-code)	Medium	122	83	205	166	288	332	386
Concrete High Rise	CHR	BT-4	Mean of C1H and C2H (pre-code)	High	122	83	205	166	288	332	386
Half Frame Low Rise	HLR	BT-1	Mean of S5L and C3L (pre-code)	Low	78	42	120	83	161	-	-
Half Frame Medium Rise	HMR	BT-1	Mean of S5M and C3M (pre-code)	Medium	78	42	120	83	161	-	-
Masonry Low Rise	MLR	BT-8	URMM (pre-code)	Low	-	42	-	83	-	-	-
Masonry Medium Rise	MMR	BT-8	URMM (pre-code)	Medium	-	42	-	83	-	-	-
Sun Dried Brick	SDB	BT-9	For SLIGHT: G. Ghodrati Amiri[16] curve, For Moderate: mean of Slight curve and heavily and Collapse curves	Low	-	42	-	83	-	-	-

be relocated and therefore it is less desirable to leave inventory un-built than to reconstruct it right away. The investment horizon was assumed to be 10 years, resulting in a per-period value of $V_{ijkt}^{cd} = 5R_{ijk}^{cd} / 10$ [1].

Our study includes five occupancy type, residential, commercial, industrial, government, education and religion (j = 5). Residential was the only occupancy type for which a complete set of data was available. For other occupancy types within the district 3 we have used other data base related to the municipality. The associated unit BI loss is also estimated based on the time required for building reconstruction and for reconstructed building and based on per period duration for un-repaired buildings. Therefore the HAZUS [7] methodology are used for these estimations. These values are presented in Table 4.

JICA[6] provided the population distribution among structural types and census zones, and it was assumed that the people per m^2 is constant across structural types and census zones so that the same distribution is true for floor area. Casualties were estimated as in JICA [6], as a function of the number of collapsed buildings, number of people per building, occupancy at the time of the earthquake, percentage of occupants trapped by collapsed buildings, percentage of occupants killed immediately by building collapse, and percentage of injured that subsequently die before rescue. It was assumed that the earthquakes occur at night and no rescue is possible. Other casualty scenarios could be incorporated with no modification in the model. The resulting values of L_{ijk}^{cd} (expected number of people who will be killed if a unit area (m^2) of building of structural type i, class m, and seismic design level c collapses) are from 0 to 0.02. Note that because the model assumes that the number of people per m2 remains constant, if the total building inventory decreases due to delayed reconstruction, it is implicitly assumed that the population declines as well, reducing future deaths as well.

The value of per statistical life was taken to be a = US$33,200, the 2006–2007 value of diyaa [17]. In Islam,

Table 4. The unit business Interruption loss for repaired or reconstructed building and un-repaired not reconstructed building

Occupancy type	The unit *BI* loss for repaired or reconstructed building (US $)			The unit *BI* loss for un-repaired not reconstructed building (US $)		
	Slight damage	Moderate damage	Heavily damage	Slight damage	Moderate damage	Heavily damage
Residential	0	9	59	0	23	23
Commercial	2	29	222	30	107	167
Industrial	0	6	23	5	18	23
Government	1	9	44	32	41	44
Education and Religion	2	17	175	65	47	67

diyaa [in Arabic: Blood money or ransom] is the compensation money paid to heirs of a victim if they decide to settle for it instead of retaliation. In Iran, as a country that follows Shariaa law, the concept of Diyaa is incorporated wherever there is a need to estimate the value of a lost life, such as in criminal charges and insurance liability cases. While this concept is controversial, it is the widely used in Iran and thus was adopted for this case study. Based on the 2005 Iran's National Report [18], Iran spends 2.5% of its annual budget on disaster reduction and mitigation efforts. Assuming half of this budget is allocated to earthquake risk reduction, since Tehran accounts for about 26% of Iran's GDP, and the total national 2005 budget was about 1,600 trillion Rials [19], we estimate a base case annual budget of Bt = US\$573 million for all t. For the Tehran's district 3 the budget assumed 1/22 of this value and therefore, B_t = US\$26. In the case analysis, the user-defined parameters were assumed to be μ= US\$33200 and κ= 0.0001.

3.3. Results

The linear optimization model was solved using CPLEX by ILOG. The results from the model can be used to answer many questions, including (1) How much should be spent on mitigation measures each year, and given those mitigation expenditures, as earthquakes happen, how much should be spent on reconstruction and how much building inventory should be allowed to not be rebuilt? (2) Which buildings should be mitigated and how? (3) Which buildings should be reconstructed and how, and which should not be rebuilt? and (4) How do the building occupancies affect the recommendations? The results can also provide insight into the complicated, interacting influences of the different geographic patterns of ground shaking caused by the many possible earthquakes, distribution of the building inventory across structural types, vulnerability of different structural types, budget constraints, and mitigation and reconstruction costs.

3.3.1. Recommended expenditures over time

Fig. 6 shows the recommended expenditures by year for the case analysis. It suggests that for the first 8 years, the most of annual budget should be spent on mitigation. In the 9th year, almost half of the total annual budget should be spent on reconstruction. In the last year, no budget recommended for mitigation and all of the total annual budget should be spent on reconstruction. If any mitigation funds will be spent on mitigation during the 10-year investment horizon, it makes sense that they be spent as early in the investment horizon as possible to maximize the number of years during which the city can enjoy the benefits of that investment (in terms of reduced earthquake damage). In this case analysis, the model recommends spending on mitigation more than reconstruction for the first years for two reasons. First, as Fig. 6 shows, while money is spent on mitigation and not reconstruction, the floor area of buildings which are not rebuilt accumulates. After 9 years, the objective to minimize lost inventory becomes relatively more important, requiring that spending switch from mitigation to reconstruction. Second, no mitigation is recommended because there is not enough time left in the investment horizon to reap the benefits of mitigation. Also, if the model is rerun with a 20-year or 30-year investment horizons instead, even the mitigation expenditures would be zero until the cumulative lost inventory gets to zero.

3.3.2. Mitigation choices

The choice of which structural types to mitigate would depend on a combination of factors, including the relative prevalence of different types in the initial inventory, the locations of buildings, the possible earthquakes, the

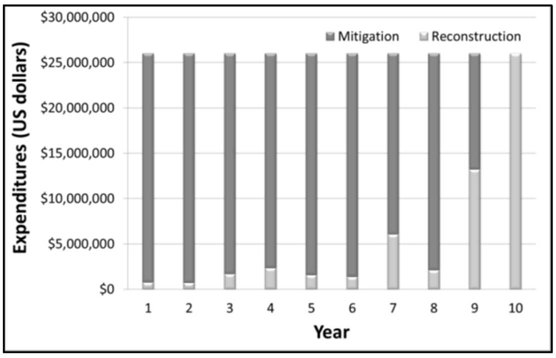

Fig. 6. Recommended mitigation and reconstruction expenditures

relative improvement in building performance achieved by mitigation, the relative vulnerabilities of these buildings, their occupancy and unit mitigation costs. Fig. 7 shows the recommended total mitigation area by initial and final structural type. Although mitigation of all building with different occupancies is possible, the mitigation recommendations allocated to residential buildings as they are considered as a places which the population dwell in order to minimize the risk of lost life. The model suggests that mostly HLR (Half frame low-rise buildings or Brick and steel (in JICA[6])) should be mitigated. Most of the building inventory in district 3 of Tehran is SLR Steel-2 51%) and HLR (24%); however HLR is more vulnerable structural type than SLR (within their respective subgroup of low-rise). Also the expected number of deaths is larger if HLR buildings damage compared to SLR buildings. Reinforced concrete (CMR) is the next most common structural type (13%) and is much more vulnerable (Fig. 4), so it is an appealing target for mitigation. Also the expected number of deaths is larger in this structural type compared to others. The choice of which structural types to be mitigated seems to

be driven largely by their relative prevalence and vulnerability of these structures and people.
The structural types selected for the buildings to be mitigated to are a function of the constraint that they must be the same height group (low- or high-rise) as the initial structural type, and a desire to choose a structural type with both low vulnerability (in structural type and people) (Fig. 4) and low mitigation cost (Table 3). All HLR is mitigated to HLR. Although mitigating to SLR, the other low-rise types, which are much less vulnerable, would also have been possible, they would have cost more (Table 3) and thus were not cost-effective.. Finally, the model does not allow Sun-dried brick to be upgraded within the same structural type; so instead, it is mitigated by rebuilding it as Steel (SLR), the most cost-effective, low-rise alternative.

3.3.3. Reconstruction choices

Fig. 8 summarizes the recommended reconstruction choices for the case analysis, by structural type reconstructed from and to. Since cumulative lost inventory remains at the end of the case analysis (10 years) (Fig. 6), some damaged buildings are eventually not reconstructed. Investigation more in the results and fig. 9 show that the reconstruction expenditures are allocated to structural buildings with commercial, education and religion and government occupancies. Therefore, the residential buildings are not the target of reconstruction. The reason is that the financial loss due to these occupancies to lose their functionality of is larger compared to the residential buildings.
As only 3 above occupancies are selected to be reconstructed, the target structural types for reconstruction depend on the prevalence of the structural types for these occupancies. Most damaged buildings which reconstructed are SMR (Steel mid-rise) which is the most common structural type in these occupancies but one of the least vulnerable. Other steel structures and half frame structural types are next choice for reconstruction, since they also make up most of the building inventory. The concrete frames are reconstructed next.

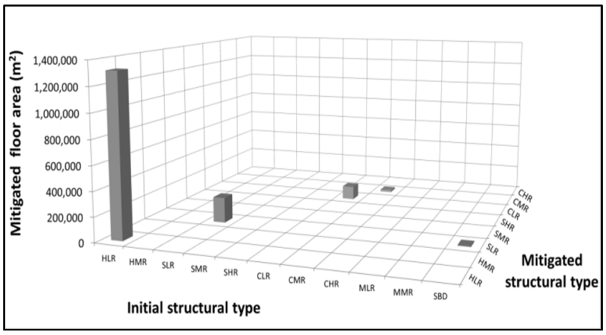

Fig. 7. Recommended mitigation expenditures by initial and final structural type

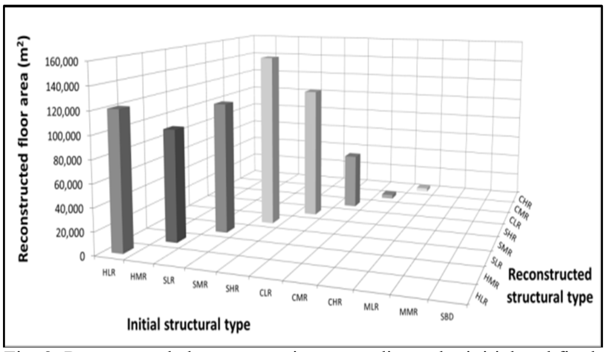

Fig. 8. Recommended reconstruction expenditures by initial and final structural type

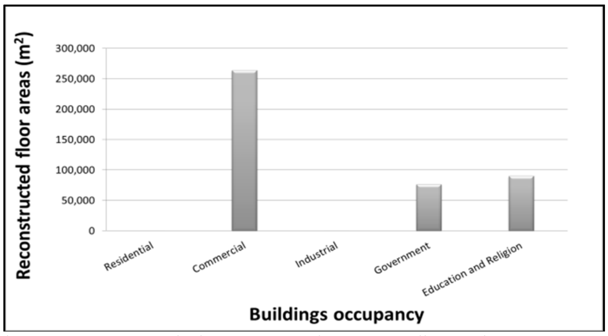

Fig. 9. Recommended reconstruction expenditures by occupancy type

4. Conclusion

Financial resource allocation and its importance in natural catastrophe risk and crises management are discussed in this paper. An introduction and historical development in natural catastrophe risk modeling and how such techniques are used by decision makers for strategic planning are discussed in this paper. Optimization process as tools for seeking optimum plans towards risk management and strategies for resource allocation are described. The paper addresses application of such approaches for minimizing adverse effects of earthquake among many plausible risk management alternatives. In this paper a regional model for resource allocation with objective of managing direct and indirect losses from future potential earthquakes is presented. The formulation for optimization process is also presented in this paper. In order to present the application of the proposed method, the approach is applied for a pilot area in Tehran. Results illustrate the mitigation expenditures are recommended to be spent on residential buildings in order to prevent life loss. The target structural types were mostly half frame buildings, steel and concrete buildings, respectively. In contrast, reconstruction expenditures are recommended to be allocated to other occupancies except residential buildings.

References

[1] P. Vaziri, Rachel A. Davidson, Linda K. Nozick and M. Hosseini, (2009). Resource allocation for regional earthquake risk mitigation: a case study of Tehran, Iran, Nat Hazards, DOI 10.1007/s11069-009-9446-4.

[2] Dodo A, Xu N, Davidson R, Nozick L (2005). Optimizing regional earthquake mitigation investment strategies. Earthq Spectra 21(2):305–327.

[3] Dodo, A., Davidson, R., Xu, N., and Nozick, L., (2007). Application of regional earthquake mitigation optimization. Computers and Operations Research 34(8), 2478-2494.

[4] Davidson, R., Nozick, L., Dodo, A., and Xu, N., (2005). Equity in regional earthquake mitigation investment. Symposium on Risk Modeling and Loss Reduction Strategies for Natural and Technological Hazards, Part of Ninth International Conference on Structural Safety and Reliability – ICOSSAR'05, Rome, Italy, June 19-23, 2005.

[5] Vaziri, P, (2009). Earthquake risk mitigation: hazard identification and resource allocation, Ph.D. Dissertation,School of Civil and Environmental Engineering, Cornell University.

[6] Japan International Cooperation Agency (JICA), (2000). "The Study on Seismic Microzoning of the Greater Tehran Area in the Islamic Republic of Iran, Final report to the Government of the Islamic Republic of Iran", Tokyo, Japan.

[7] Federal Emergency Management Agency (FEMA), (1999). Chapter 15 : "Direct Direct Economic Losses", HAZUS99-SR2 Technical Manual, FEMA, Washington D.C.

[8] Graham J, Vaupel J, (1981). Value of a life: what difference does it make? Risk Anal 1(1):89–95.

[9] International Monetary Fund (IMF) (2007) IMF executive board concludes 2006 article IV consultation with the Islamic Republic of Iran, Public Information Notice (PIN) No. 07/29. Available at: http://www.imf.org/external/np/sec/pn/2007/pn0729.htm, Accessed 17 June 2008.

[10] Ramazi H (1999) Attenuation laws of Iranian earthquakes. In Proceedings 3rd International Conference on Seismology and Earthquake Engineering, Tehran, pp 337–344.

[11] Sarma S, Srbulov M (1996) A simplified method for prediction of kinematic soil-function interaction effects on peak horizontal acceleration of a rigid foundation. EarthqEngStructDyn 25(8):815–836.

[12] Ambraseys N, Bommer J (1991) The attenuation of ground acceleration in Europe. EarthqEngStructDyn 20(12):1179–1202.

[13] Management and Planning Organization (MPO) of Iran (2007) instruction for rehabilitation of existing buildings, Monograph No. 360, Office of Deputy for Technical Affairs, MPO.

[14] Federal Emergency Management Agency (FEMA) (2000) Prestandard and commentary for the seismic rehabilitation of buildings, FEMA 356, prepared by the American Society of Civil Engineers for FEMA, Washington.

[15] Peyghaleh E, Zolfaghari MR, (2013), Implementation of Equity in Resource allocation for Regional Earthquake risk Mitigation using Two-Stage Stochastic Programming, under review.

[16] Ghodrati-Amiri, G., Jalalian, M. and Razavian-Amrei, S.A. Derivation of Vulnerability Functions Based on Observational Data for Iran. Proceedings of the International Symposium on Innovation & Sustainability of Structures in Civil Engineering; 2007 November 28-30; Shanghai, China. Paper No. 227.

[17] Iran Ministry of Justice (2006) Internal circular on Diyaa in regards to article 297 of the Islamic Penal Code.

[18] Iran (2005a) National budget act of 1384, 2005. Available at: http://www.spac.ir/hoghoghi, Accessed 15 May 2008.

[19] Iran (2005b) National report of the Islamic Republic of Iran on disaster reduction, world conference on disaster reduction, Kobe, Japan. Available at: http://www.unisdr.org/eng/mdgs-drr/national-reports /Iranreport.pdf, Accessed 4 May 2008.