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A New Method for Assessing the Seismic Risk of Urban Fabrics in Iran

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ABSTRACT

In order to reduce the seismic risk in urban fabrics effectively, it is necessary to make a comprehensive assessment of vulnerability and seismic hazards in different parts of the urban area. This could provide essential information for city managers and decision makers for better understanding of risk mitigation priorities. Since in most cities of Iran, the required data are usually unavailable or inadequate, estimation of absolute risk is not possible. In this paper, a simple and comprehensive methodology is introduced to estimate the relative seismic risk among urban zones instead of absolute risk. For this purpose, parameters with significant contribution to seismic risk are selected and classified into physical, human life and socio-economic categories. The seismic risk associated to indicators of each category is estimated according to the vulnerability and relevant hazard factors. It can conceptually reduce uncertainties in combination of earthquake hazard and vulnerability through definition of separate hazard factors. The effect of response capacity and recovery capability are also considered in estimation of total risk; however, relevant methodology and parameters of this item are now under study. Finally, the model is applied to estimate the seismic risk of Tehran at district level, and results are compared to other works. Considering the impacts of all presented indicators, results of the proposed model show that district 15 has the highest rank of seismic risk in Tehran Metropolitan area.

Keywords:
Relative seismic risk; Physical vulnerability; Socio-economic condition; urban fabrics; Iran

1. Introduction

The exponential increase in the world's population, along with the growth of big cities and improper occupancy of the land increase the damage potential due to seismic events. The high density of population, buildings, infrastructures, and exposed vulnerable elements turned these zones into high-risk areas. Furthermore, lack of sufficient management and planning programs in addition to the economic and social problems increase the vulnerability of the urban fabrics against earthquake related hazards. Seismic risk in an urban area is a non-linear combination of earthquake hazards and the vulnerability state of exposed elements [1]. Therefore, it is necessary to make a comprehensive assessment of vulnerability and seismic hazards to make appropriate decisions for reducing the consequences of the earthquake in urban areas.

In this paper, a comprehensive seismic risk assessment approach has been proposed for urban areas. For this purpose, by reviewing previous investigations in this field (section 2), physical and socio-economic parameters that mostly contribute to seismic risk estimation of urban environment are selected and categorized in three groups of physical, human life and socio-economic indicators. In addition, earthquake relevant hazard factors are described and classified according to the vulnerability groups (section 3.1 and 3.2). Indicators of risk associated to each vulnerability indicator are defined as a combination of vulnerability and hazard factors (section 3.3). The contribution of response capacity in urban areas is also considered in total risk estimation; however, the relevant methodology and parameters to determine this item are now under study. Subsequently, a scaling method is presented to normalize the gross value of each indicator (section 3.4). The total relative risk index is then defined as a weighted combination of the risk and response capacity indicators (section 3.5). Finally, In order to evaluate the effectiveness of the proposed model, a case study is carried out for assessing the seismic risk of Tehran at district level (section 4). A brief discussion is presented in section (5) to explain the capabilities and advantages of the proposed methodology.

Since the proposed method estimates the relative seismic risk instead of absolute risk, it utilizes simple and indirect approaches to evaluate the risk and vulnerability indicators. Therefore, for cities in which the required data to estimate the absolute amount of loss and casualties are not available, the method can be used for the assessment of the relative risk, and appropriate allocation of limited resources in priority programs for risk reduction.

2. Background

There are many methods for assessing the vulnerability of urban fabrics using physical, social, economic and other parameters at local, regional, national and international levels. Examples of risk assessment methods incorporated with vulnerability analysis at different scales can be found in literatures. Earthquake Disaster Risk Index (EDRI) presented by Davidson and Shah [2] describes a multidisciplinary approach by considering several aspects of seismic risk and vulnerability. Since EDRI has been developed for the comparison of relative risk among different cities (city scale), risk and vulnerability indicators are quantified implicitly. Thus, their proposed indicators are not appropriate to assess the risk in local scales. In Radius project [3], earthquake risk for different cities selected from Asia, Europe, Middle East, Africa, and Latin America is assessed by considering some of the main physical urban parameters such as buildings, infrastructures, etc.; however, this approach did not include social and economic issues that may affect the risk significantly. One of the comprehensive urban earthquake risk assessment approaches is HAZUS [4], which was developed by FEMA-NIBS. This method considers socio-economic aspects of urban risk as well as buildings, lifelines, transportation and infrastructures, but its application is limited as it is designed for the United State conditions. Similarly, many other approaches have been developed in Europe to assess earthquake risk and losses for Euro-Mediterranean region. The final products of these studies are usually presented as software packages (e.g. SELENA, SAFER, Risk-UE). These software normally cannot be applied for other regions of the world, as their approach and assumptions are not consistent for them. The comparison and discussion on the application of these software are given by Daniell [5]. Cardona et al [6-7] developed a model for the seismic risk analysis of urban areas from a holistic view. This model takes into account physical risk, exposure and socio-economic characteristics of different urban units as well as their disaster coping capacity or degree of resilience. This helps to identify the critical zones of a city and their vulnerability with a multidisciplinary point of view. However, many parameters such as lifeline's vulnerability and interaction, and socio-economic vulnerability are not considered sufficiently.

Khazai et al [8] proposed a methodology based on the approach of Cardona [6] to estimate the risk of earthquake in Istanbul. They defined the social vulnerability (SV) and disaster risk management (DRM) indicators to consider the effects of social fragility, lack of resilience and capacity of different operational and organizational policies in urban districts. Although some appropriate socio-economic aspects were considered in their study, evaluation of some indicators need questionnaire data collection that is not simple to carry out in each city.

Amini-Hosseini et al [9-10] evaluated the seismic vulnerability of Tehran by considering some of the physical and socio-economic parameters. They compared the results with existing plans and programs for rehabilitation of the old urban fabrics in Tehran prepared based on the regulations of ministry of Housing and Urban Development of Iran (HUDI). The results show that the prepared plans based on only physical vulnerability cannot properly identify the priorities for rehabilitation of urban fabrics. Thus, it is necessary to consider the role of earthquake related parameters as well as socio-economic conditions for identification of vulnerable areas. However, this approach was not quantified by some measurable variables.

Duzgun et al [11] considered the vulnerability of urban environment in a holistic viewpoint and performed the vulnerability assessment at the neighborhood scale. Their methodology integrated socio-economic, structural and coastal parameters as well as ground condition, vulnerabilities and accessibility to critical services. However, it did not pay enough attention to earthquake coping capacity of urban area, which cannot be estimated easily in neighborhood scale.

Frolova et al [12] assessed the expected loss and damage caused by earthquakes and secondary technological accidents. They also considered the vulnerability of buildings due to ground motion as well as secondary hazards such as fire, explosion and chemical hazardous facilities triggered by strong seismic events. Besides, they considered the vulnerability of the population as a ratio between the numbers of persons affected and the total number of persons living in a certain type of buildings. Accordingly, the risk has been determined based on social losses, which include fatalities, injuries and property losses. Meanwhile, it also measured the number of inhabitants in assumed settlements. Although an appropriate method were used in this study for estimation of human losses, other features of urban risk such as physical, socio-economic and response capacity were not included.

Among recent studies, SYNER-G [13] explained vulnerability analysis and loss estimation as well as socio-economic vulnerability in order to quantify earthquake impacts considering interdependencies within system units and among different systems to estimate the increased loss impacts.

Most of the introduced approaches are not comprehensive for seismic risk estimation in urban areas, as they did not take into account all aspects of risk (physical, socio-economic and response capacity). However, in some other studies in spite of employing comprehensive approaches (e.g. HAZUS, Syner-G), they need to have large amount of information and data or they were designed for special countries with their specific conditions or in the large scales (city or region). Therefore, in this paper, we present a new approach that not only takes into account the socio-economic aspects, but also it can evaluate the vulnerability and risk in local scales (neighborhood to district scale) with limited information and data.

3. Framework of the Proposed Methodology

In order to perform a comprehensive assessment of earthquake risk in urban areas, sufficient information about existing earthquake hazards at each zone should be gathered. Furthermore, it is essential to consider the vulnerability of all relevant elements of the area exposed to those hazards. Then, the seismic risk can be evaluated by taking into account the state of vulnerability and hazard. Figure (1) shows the proposed procedure to estimate the relative seismic risk index in urban areas.

The proposed approach estimates the relative seismic risk in urban and sub-urban scales (from neighborhood to district) through the following steps:

- Selection of the most important earthquake related hazards for evaluation of hazard factors using the existing data and information (i.e. probable ground motion, ground failure and the potential of secondary hazards);
- Assessment of the physical, human life and socio-economic vulnerability and response capacity indicators and their relevant components that significantly contribute to seismic risk of urban environment;
- Scaling gross values of indicators and their components;
- Determination of importance weight factors for each indicator and its parameters;
- Evaluation of risk and response capacity indices through integration of vulnerability indicators and hazard factors as well as considering response capacity indicators;
- Evaluation of the total relative risk index via a weighted combination of risk and response capacity indicators.

As depicted in Figure (1), once the total relative risk is estimated, managers and policy makers can understand the influence and contribution of each parameter in seismic risk. Consequently, they can

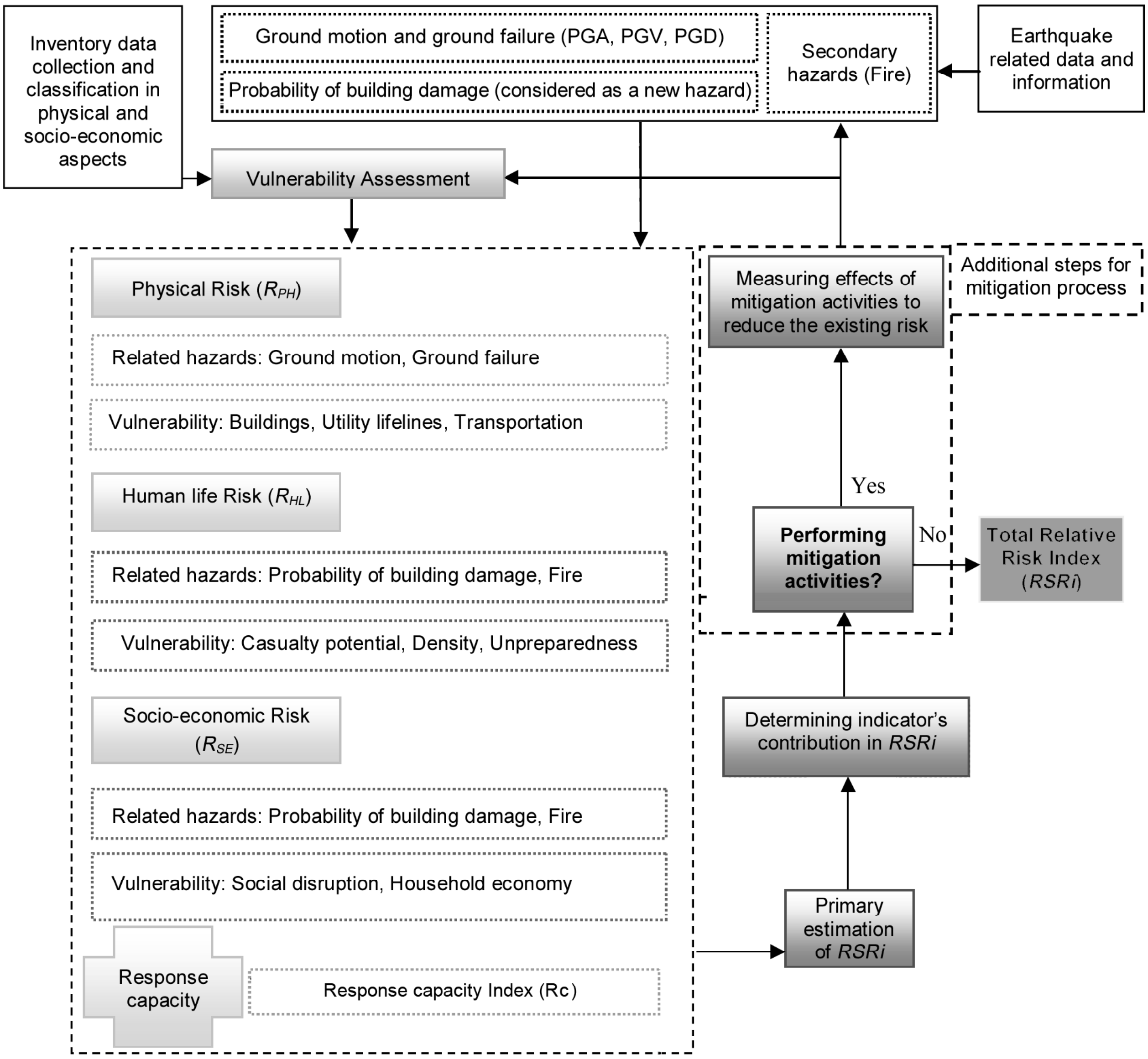


Figure 1. Proposed procedure to estimate the Relative Seismic Risk index (RSRi).

take some mitigation strategies according to their resources. After that, by measuring the effect of mitigation strategies, input parameters of the model can be changed based on new condition, and the total risk can be reassessed to estimate the effectiveness of applied activities and programs. In the proposed approach, importance weights of indicator and their relevant components are determined using the AHP (Analytical Hierarchy Process) method [14], which is used to derive weights from both discrete and continuous paired comparisons. In this method, questionnaires are prepared and filled by relevant experts using the Delphi method. This is an appropriate way of judging the relative importance of variables having different nature and estimating their relative weights [6]. Moreover, in some cases, engineering judgment is employed for determining the weights.

3.1. Estimation of Hazard Factors

Hazard factors are coefficients that are combined with vulnerability indicators to estimate risk indicators. In this research, a separate factor of hazard is defined regarding to each component of vulnerability. For this purpose, besides of ground motion parameters *H*1 (PGA, PGV and Intensity), three other types of hazards probable to occur due to ground motion are considered in assessing the hazard factors, Table (1). Components of ground failure hazard (surface fault rupture, subsidence, landslide and liquefaction) are placed in one group (*H*2) assuming to have similar effects on structures and lifelines. The effect of *H*2 is measured by means of Permanent Ground Deformation (PGD) parameter [4].

Table 1. Earthquake related hazard factors.

Hazard Factor	Components
H1	Ground motion (PGA, PGV, intensity)
H2	Ground failure (subsidence, liquefaction, etc.) (PGD)
H3	Probability of building damage/collapse
H4	Secondary hazards (Fire)

In order to have a better estimation of risk, various effects of these individual hazard indicators should be recognized and respected. For example, ground motion and ground failure hazards are not direct threats of human life, whereas, they are main threats for physical elements such as buildings. Since the significant cause of human casualty is the building damage (due to its vulnerability) rather than ground motion hazard, probability of building damage is considered individually as a new hazard factor (*H*3), and estimated by Eq. (1). *H*3 can also represent the hazard of fire initiation due to damages of gas and electricity networks inside the buildings.

$$H3 = P_C + 0.8P_S + 0.45P_E + 0.15P_{SM} \tag{1}$$

In Eq. (1), P_C, P_S, P_E, and P_{SM} are average probabilities of experiencing (but not exceeding) damage states of collapse, complete (or severe), extensive and slight-to-moderate respectively in various building types according to their floor area. The relevant weights are determined by engineering judgment. Similar to *H*3, secondary hazards such as fire (*H*4) are defined separately, because the fire initiation does not necessarily follow the distribution of physical damages, Eq. (2). In fact, it can be said that *H*3 and *H*4 are dominant threats for human life in an urban area (since the inundation hazard is not considered in this study).

$$H4 = (1.0 + HM) \times (GD + ED)/4 \tag{2}$$

In Eq. (2), *GD* and *ED* are factors associated to physical damage of gas and electricity networks respectively. *HM* is a factor that represents the number of hazardous facilities (e.g. gas stations) inside the urban zone and takes value between 0 and 1.0. In addition, an Equivalent Hazard factor (*EH*) is defined by integration of *H*3 and *H*4. *EH* addresses an earthquake related hazard, which directly causes casualties and socio-economic disruptions, Eq. (3).

$$EH = 0.7\,H3 + 0.3\,H4 \tag{3}$$

In this equation, *H*3 and *H*4 are hazard factors associated to building damage and fire initiation respectively. Since the hazard of fire is usually limited and it may not initiate essentially during the disaster, the importance weight of *H*4 is considered as 0.3 (in comparison with 0.7 for *H*3). All of the hazard factors (*H*3, *H*4 and *EH*) take values between 0 and 1.0.

3.2. Proposed Indicators for Vulnerability Assessment

In this research, some simple, measurable and scalar indicators are selected to represent and compare the seismic risk of urban zones. For this purpose, the vulnerability, as the most important part of seismic risk, is classified in three main categories: Physical, Human life and Socio-economic vulnerabilities. These categories and their relevant indicators and sub-component as well as their importance weight (*w*) are introduced and presented in Table (2) as follows:

Physical vulnerability: In earthquake situation, the vulnerability of physical elements of an urban area (buildings, utility lifelines and transportation systems, etc.) will result in direct and indirect losses. Furthermore, it is the main cause of human casualties and social disruptions. Three indicators of building, utility lifelines and transportation vulnerabilities are proposed to characterize the physical vulnerability.

Human life vulnerability: Reducing the human casualties of potential earthquake is the main goal of risk mitigation and management planning. In this research, three factors that mainly affect the human casualties are considered. The casualty potential due to building damage is considered as the main indicator. The density of population and buildings, and the preparedness level of people, are other indicators that are proposed to consider the difficulty of evacuation and self-rescue in time or just after the disaster.

Socio-economic vulnerability: After destructive earthquakes, the disruption of social and economic activities is inevitable. Improving the safety and security of the city, adjusting production and distribution of essential materials and controlling political and economic effects of the earthquake in and out of the area are some of the socio-economic issues that should be considered in this part. Two

Table 2. Three main categories of vulnerability.

Main Category (Index)	Sub-Components (Indicators)		Vulnerability Characteristics
Physical Vulnerability (V_{PH}) (w_{PH} = 0.30)	$V1$: Building vulnerability	w = 0.60	Building structure and occupancy type
	$V2$: Utility lifeline vulnerabilit	w = 0.30	Lifelines network characteristics
	$V3$: Transportation vulnerability	w = 0.10	Road network characteristics
Human Life Vulnerability (V_{HL}) (w_{HL} = 0.50)	$V4$: Casualty potential	w = 0.75	Population distribution in various structures and occupancies
	$V5$: Density	w = 0.15	Density of population and buildings
	$V6$: Unpreparedness (of people)	w = 0.1	Age distribution
Socio-economic Vulnerability (V_{SE}) (w_{SE} = 0.20)	$V7$: Social disruption potential	w = 0.5	Delinquency, social cohesion, education , socio-economic importance of zone
	$V8$: Household economic vulnerability	w = 0.5	Income, employment, ownership, household dimension

(w: importance weight)

indicators are selected for this assessment; social disruption indicator that shows the disorders and violence of people, and household economic vulnerability that represents the economic resiliency of households.

The simple additive weighting method (SAW) is used, Eq. (4), to estimate the value of each index, indicator and sub-indicators by considering the importance weight of its relevant components.

$$K = \sum_{i=1}^{n} w_i \times k_i \tag{4}$$

where K is the value of index, indicator or sub-indicator of physical vulnerability, human life vulnerability, socio-economic or response capacity. Parameter n is the number of sub-components (k) of K, and w is the importance weight (between 0 and 1.0), respectively.

3.3. Estimation of Risk Indices

In order to estimate the relative seismic risk index, values of risk indicators should be integrated according to their importance weights. As stated before, risk is a combination of hazard and vulnerability [1]. In this research, risk indicators associated to physical vulnerability and human casualty indicators ($V1$ - $V4$ in Table (2)) are estimated by employing fragility functions, which usually use ground motion parameters ($H1$) as for hazard factor. By using these functions, the vulnerability and hazard parameters are integrated through a non-linear (such as logarithmic [15]) function. However, in case of other vulnerability indicators ($V5$- $V8$ in Table (2)), the risk indicator is estimated by multiplication of vulnerability by the Equivalent Hazard factor (EH). Then, physical, human life and socio-economic risk indices are calculated through weighted combination of their relevant indicators. In following sections, the proposed approach for evaluation of risk and vulnerability indicators is explained.

3.3.1. Evaluation of Physical Risk Index (R_{PH})

The risk in physical part of a city is defined as an integration of seismic hazard and vulnerability of physical elements (buildings, lifelines and transportation facilities). The physical risk index is quantified as:

$$R_{PH} = w_{Buildings} \times R_{Buildings} + w_{Lifelines} \times R_{Lifelines} + w_{Transportation} \times R_{Transportation} \tag{5}$$

where R and w are values of risk and importance weight associated to indicators of physical risk ($V1$- $V3$ in Table (2)).

3.3.1.1. Building Risk Indicator ($R_{Buildings}$):

This indicator is estimated based on losses due to building damages (structural, non-structural and content loss as well as debris removal cost). Due to the complication of calculations and normally insufficient data, the absolute amount of losses is very difficult to be estimated in urban scale. Therefore, in this study, a simple procedure is developed to evaluate relative losses in city zones. The information and required data that should be provided for this purpose are:

- Floor area of each type of building's structure and occupancy types;

- Floor area percentage of each building's structure type in each occupancy type;

Tables (3) and (4) illustrate building typology and occupancy classes considered in this study. The building's structure typology is adopted from JICA study for Tehran [16], and classification of occupancy types is adapted from HAZUS methodology [4]. Each type of building structure is considered in three classes of height according to its number of stories as; low rise with 1 to 3, mid-rise with 4 to 7 and high-rise buildings with more than 7 stories.

It is assumed that effects of other hazards except ground motion are not significant in damage of buildings. Thus, common fragility curves based on PGA are employed to assess this indicator. Therefore, by knowing the amount of hazard (here only $H1$: PGA), fragility curves calculate the probability of any particular building experiencing each of the damage states. The state of building damage is classified into four groups of collapse, complete (or severe), extensive and slight-to-moderate levels.

Several methods are presented in order to estimate damage states and collapse rates of buildings (e.g. [4, 15, 17, 18]). Most of them use building damage data of the earthquakes in different regions of the world and the parameters of relevant fragility curves are determined based on relevant empirical data. Therefore, for each region, it is appropriate to develop such curves with respect to its own buildings materials and construction types. Accordingly, in the proposed model, parameters of building fragility curves are determined using researches carried out for building types in Iran [19]. Furthermore, in the present study as a necessity, we conduct a new research to determine the collapse rate (rate of probable collapse among severely or completely damaged buildings) for each building type in Iran. For this purpose, data and information of damaged buildings in 2003 earthquake of Bam, Iran are gathered from previous studies carried out by Hisada et al [20] and Mostafaei et al [21].These databases contain information of damage states of more than 1450 investigated buildings. In addition, the earthquake intensity distribution in Bam city is derived from these works and the study carried out by Tobita et al [22].

Table 3. Structural typology.

Structure Type	Description
Adobe	Adobe structures
Masonry 1	Weak masonry building structure composed of brick wall and partial frames in which earthquake resistance capacity is ignorable.
Masonry 2	-Unreinforced Masonry: A simple masonry building type composed of bricks, natural stones or concrete blocks. -Semi-Engineered Masonry: Stands for the masonry structure with common RC frame, in which earthquake resistance capacity is not sufficient.
Steel 1	Steel frames with poor welding and insufficient seismic capacity of beams, columns and joints.
Steel 2	Steel frame with relatively good seismic resistance.
RC 1	Reinforced concrete frames with insufficient seismic capacity of beams, columns and joints.
RC 2	Reinforced concrete frames with relatively good seismic resistance.
Other Types	Like wood, …

Table 4. Types of occupancy classes.

Occupancy Type	Description
Public	Mosques, public halls, …
Residential	Houses, apartments, hotels, dormitories, …
Commercial	Shopping centers, service centers, warehouses, entertainment and recreations places, …
Industrial	All type of factories, workshops, …
Governmental	Offices, banks, …
Educational	Schools, colleges, universities, …
Response facility	Fire stations, hospitals, police stations, medical offices, clinics, …
Other types	Farm lands, open spaces, parks, sport fields, …

Results of our study demonstrate a relation between collapse rate and ground motion parameters (PGA and intensity). The observed variation of collapse rate with intensity for all building types is approximately linear in the range of 8 to 10 MMI. This is in contrast to the proposed rates by HAZUS [4], which present a constant collapse rate for each building type. Moreover, in order to eliminate the uncertainties associated with determination of ground motion parameters, the variation of collapse rate by the percentage of severely damaged buildings is surveyed. For this purpose, the collapse rate is related to the percentage of severely damaged structures by means of a linear function. However, the characteristics of this straight line are different for various building types. The detailed results of this survey will be presented in other papers.

When the damage state of buildings is determined in urban zones, the amount of loss due to these damages should be estimated. In this study, a simple method is presented to estimate the relative loss associated to building damage according to occupancy type and other non-structural elements of buildings. The relative loss value is defined as the relative cost (between 0: the lowest and 1.0: the highest cost) needed for repairing or constructing a new common structure with the same characteristics. Table (5) shows the relative loss value (*RL*) associated to structural damage determined by expert opinion and engineering judgments for each type of building in Iran. It is assumed that in the case of collapse and complete damage, all types of buildings would be reconstructed similarly by considering their previous floor areas and number of stories. Therefore, this value for all types of buildings with the same class of height is equal to 1.0.

Other types of loss related to damage of buildings such as debris removal, non-structural and building content damage are also included in this part, and their relevant factors are multiplied by *RL*. The total relative loss of buildings ($R_{Buildings}$) is then defined by the combination of relative loss values for all types of structures, according to their damage states and height classes as:

$$R_{Buildings} = TFA \times \left\{ \sum_{i=1}^{8} \sum_{j=1}^{3} \alpha_j \times PFA_{ij} \times \left[\sum_{k=1}^{4} RL_{ik} \times (C_i + N_i + D_i) \right] \right\} \tag{6}$$

where *i*, *j*, and *k* belong to varieties of structure types, height types and damage states respectively. *TFA* is the total floor area of buildings in urban zone, and *PFA* is the floor area percentage of each structural type according to its height class. α is a factor that interprets the difference of loss due to the story (height). For low, mid and high-rise structures, this value is assumed as 1.0, 1.15 and 1.3, respectively. It means that, constructing a high-rise structure is 30 percent more expensive than a low-rise structure with the same floor areas. *D* is a factor that represents the relative cost of debris removal, Table (6), among structural types. *C* and *N* are factors of relative content and non-structural losses, among structural types. Values of *C* and *N* are calculated for each structural type by mapping the structure and occupancy data and using Table (7). These three factors (*D*, *C* and *N*) are determined using the methodology of HAZUS [4], and the relative value for each factor is between 0 and 1.0.

Table 5. Relative loss (RL) of building structure damage.

Structure Type	**Damage State**			
	Slight-Moderate	**Extensive**	**Complete**	**Collapse**
Adobe	0.07	0.28	1.0	1.0
Masonry 1	0.13	0.57	1.0	1.0
Masonry 2	0.13	0.57	1.0	1.0
Steel 1	0.17	0.71	1.0	1.0
Steel 2	0.17	0.71	1.0	1.0
RC 1	0.20	0.85	1.0	1.0
RC 2	0.20	0.85	1.0	1.0
Other types	0.15	0.65	1.0	1.0

Table 6. Debris removal cost Factor (D).

Structure Type	D
Adobe	1.00
Masonry 1	1.00
Masonry 2	1.00
Steel 1	0.80
Steel 2	0.45
RC 1	0.90
RC 2	1.00
Others	0.30

Table 7. Factors of Content loss (C) and Non-structural loss (N).

Occupancy Type	C	N
Public	0.65	0.90
Residential	0.35	1.00
Commercial	0.65	0.80
Industrial	1.00	0.80
Government	0.65	0.90
Educational	0.75	1.00
Response Facility	1.00	0.95
Others	0.65	0.50

3.3.1.2. Utility Lifelines Risk Indicator ($R_{Lifelines}$):

Utility lifelines in an urban area include different nodes and links of water, electricity, gas and telecommunication systems. In order to estimate the seismic risk, the vulnerability of these systems should be determined. In this research, the vulnerability of nodes (e.g. lifeline's structures) is not considered in estimation of lifelines risk, and only the vulnerability of links is investigated. Thus, for simplification, it is assumed that the relative risk for each lifeline system would be the same as the amount of relative risk of its network's link.

In order to evaluate the interruption risk or serviceability reduction of total lifeline system after the earthquake, the functionality of each lifelines' system and the interaction effects among them should be assessed. In this study, the interruption risk of utility lifelines is estimated by four steps based on the methodology proposed by Selva et al [23]:

- Step 1: FC (Fragility Curve of components)→ *PD* (Physical Damages of components).
- Step 2: PD → PNF (Physical Non-Functionality of systems due to physical damages).
- Step 3: PNF → ANF (Actual Non-Functionality of systems due to the interaction effect among lifeline systems).
- Step 4: ANF → Risk (the interruption risk of overall system).

At the first step, the physical or direct damage to each lifeline system would be assessed using damage functions [24-26]. Hazard factors for this assessment are *H*1 and *H*2. Table (8) shows the type of network's link, hazard factor and fragility relations used to estimate physical damage of each lifeline system. In this table, Repair Rate (RR) is defined as the number of breaks or leaks initiated along the pipe length due to ground motion or ground failure. When damage to pipeline is initiated by PGV, it is assumed that 80 percent of repair points are leaks and 20 percent are breaks. However, when the damage to pipeline is initiated from ground failure (PGD), the ratio is assumed to be 20 and 80 percent for leaks and breaks respectively [4].

Subsequently, the damage algorithm proposed by HAZUS [4] is used for the evaluation of the performance (functionality) of each lifeline system. Therefore, the system performance level is estimated by a "conjugate" lognormal function (i.e., 1.0-lognormal function). This damage function has a median of 0.1 (repairs/km) and beta of 0.85. The only variable of this function is the "average break rate", which can be computed by division of total break points by total pipe length. The non-functionality of these

Table 8. Damage estimation methods for each lifeline network.

Lifeline System	Network's Link Type	Hazard Factor	Damage Function	Employed Model
Water (PW)	Buried Pipelines	H1:(PGV)	$RR^{*}=K1x0.0001xPGV^{2.25}$	O'Rourke and Ayala [24]
		H2:(PGD)	$RR=K2x7.821xPGD^{0.56}$	Honegger and Eguchi [25]
Gas (NG)	Buried Pipelines	H1:(PGV)	RR=K1x0.002416xPGV	ALA [26]
		H2:(PGD)	$RR=k2x2.5831xPGD^{0.319}$	ALA [26]
Electricity (ES)	Distribution circuit	H1:(MMI)	Empirical method based on Intensity	JICA [16]
Tele (TC) Communication	Distribution circuit	H1:(MMI)	Empirical method based on Intensity	JICA [16]

(Repair Rate (RR) = number of repairs/km) systems is then calculated as “one minus performance factor”. Then, the Non-functionality of network is assumed to be proportional to the ratio of damaged length of cables. When the state of non-functionality is estimated for each type of lifeline network, the actual non-functionality (*ANF*) can be assessed by considering the interaction effect among different lifelines. For this purpose, the method proposed by Alexoudi et al [27] can be employed. In this method, “the matrix of impact factor” that explains the effect of functionality of each lifeline on other systems is defined based on the economic relation between them. However, the required data is not available for using this method. Therefore, in this study, interaction factors are determined by engineering judgment, Table (9).

Table 9. Interaction Factors (IF) (effect of lifeline j on i).

Lifeline j / Lifeline i	ES	PW	NG	TC
Electricity (ES)	1.0	0.1	0.1	0.3
Potable Water (PW)	0.7	1.0	0.1	0.3
Natural Gas (NG)	0.3	0.1	1.0	0.3
Telecommunication (TC)	0.3	0.3	0.1	1.0

Finally, the actual non-functionality (*ANF*) for each lifeline system is calculated as:

$$ANF_i = PNF_i \times (1 + \sum_{j=1}^{3} IF_{ij} \times PNF_j) \qquad (7)$$

where PNF_i is physical non-functionality of lifeline system i that its actual non-functionality (*ANF*) is calculated; and j corresponds to the three other lifeline systems ($j \neq i$) with interaction factor *IF*. The risk or non-functionality of total lifeline system in urban zone ($R_{Lifelines}$) is then calculated through the combination of *ANFs* as:

$$\begin{aligned} R_{Lifelines} = {} & 0.45(Lne_{Electricity}\ ANF_{Electricity}) + \\ & 0.25(Lne_{Water}\ ANF_{Water}) + \\ & 0.15(Lne_{Gas}\ ANF_{Gas}) + \\ & 0.15(Lne_{Telecomunication}\ ANF_{Telecomunication}) \end{aligned} \qquad (8)$$

Here, *Lne* is a factor that represents the relative lenght of each network in urban zone. The weights factors for electricity, water, gas and telecommunication systems are approximately estimated based on engineering judgments.

3.3.1.3. Transportation Risk Indicator ($R_{Transportation}$)

In order to assess the risk of physical damage in transportation system (here only road network), urban roads are divided into three groups: Narrow roads (less than or equal to 6 meters width), Minor roads (width of 8 to 15 meters) and Major roads (widths greater than 15 meters). In this study, the physical damage (*DF*) of minor and major roads (i.e. damage due to permanent ground deformation) is calculated using fragility curves adapted from HAZUS [4], Table (10). Moreover, it is assumed that fragility parameters of narrow roads are similar to minor roads. Then, the transportation risk indicator ($R_{Transportation}$) is estimated by combination of damage factors of narrow, minor and major roads:

$$\begin{aligned} R_{Transportation} = {} & Lr_{Major} \times DF_{Major} + (w_{Minor}/w_{Major}) \times \\ & Lr_{Minor} \times DF_{Minor} + (w_{Narrow}/w_{Major}) \times \\ & Lr_{Narrow} \times DF_{Narrow} \end{aligned} \qquad (9)$$

where *DF*, *Lr* and *w* are damage factor, length ratio and average width of each road type, respectively.

Table 10. Fragility curve parameters for major and minor roads (adapted from HAZUS [4]).

Road Type	Mean Value of PGD (cm) for Each Damage State			Standard Deviation
	Slight	Moderate	Extensive/ Complete	
Minor (8 to 15m Width)	15	30	60	0.7
Major (More than 15m Width)	30	60	150	0.7

3.3.2. Evaluation of Human Life Risk Index (R_{HL})

Reducing the human casualties is the main goal of seismic risk mitigation plans in urban fabrics. Since casualties mostly arise from building damages, vulnerability of structures in different urban land uses is considered as the main component for assessment of human life risk. Moreover, the rescue and relief services provided soon after the disaster have a substantial effect on casualty level. Thus, two parameters, i.e. density of population and buildings, and preparedness level of people, are also proposed to characterize this index. Information and required data that should be provided for evaluation of human life risk indicator are:

- Population distribution in each occupancy type in three times of a day (earthquake scenarios: 2 a.m., 2 p.m. and 5 p.m. or peak of traffic time in afternoon);
- Maximum population usually attend in each occupancy type during 24 hour;
- Disaster weak population distribution (under 5 and above 65 years old);
- Proportion of dynamic and static population;
- Rates of unemployment, delinquency and educated population;

Finally, the risk of human life (R_{HL}) is estimated according to seismic hazard and human associated vulnerabilities as:

$$R_{HL} = w_{Casualty} \times R_{Casualty} + w_{Density} \times R_{Density} + w_{Unpreparedness} \times R_{Unpreparedness} \tag{10}$$

where three risk indicators of casualty (due to buildings damage), density and unpreparedness ($V4$-$V6$ in Table (2)) are summed according to their importance weights (w).

3.3.2.1. Casualty Risk Indicator ($R_{Casualty}$)

This indicator is determined based on the amount of casualties resulting from building damage in earthquake. Again, in this study, due to the complication of calculations and lack of required data, relative amount of human casualties is determined instead of absolute amount. For this purpose, damage of structures is assumed as the main hazard factor and effects of other hazards (i.e. ground failure, secondary hazards…) are not considered. Besides, according to the study of Ghayamghamian et al [19], casualties are classified in three states of death, severe injury and slight injury, and the probability of each casualty state is computed based on the state of damage and casualty rate of each building typology in Iran [19].

In addition, according to the fact that the distribution of population in urban land uses is different during the day and night, the presence of people in every land uses are considered for three scenario times (2 a.m., 2 p.m. and 5 p.m.: peak of traffic time in afternoon). Table (11) shows the default distribution of indoor population rate adapted from studies of Mansouri et al [28] and HAZUS [4]. The coefficients of this table would be multiplied by maximum population of relevant occupancy types to calculate the maximum indoor population. The maximum attending population of each occupancy type is calculated according to total population, floor area of occupancy classes and dynamic over static population in each urban zone. Accordingly, the distribution of population in each type of structures in various times of the day would be determined using Table (11) and information gained from mapping land use and structure type distributions. Then, using casualty rates and results of building damage estimation, casualty states for each type of structures are calculated for each damage state.

Table 11. Indoor population rates.

Occupancy Type	Scenario Time of Earthquake		
	2 a.m.	**2 p.m.**	**5 p.m.**
Public	0.01	0.80	0.50
Residential	0.99	0.47	0.56
Commercial	0.02	0.98	0.50
Industrial	0.10	0.80	0.50
Governmental	0.02	0.98	0.10
Educational	0.001	0.80	0.50
Response Facility	0.50	0.98	0.75
Other Types	0.10	0.80	0.50

Finally, in order to define a unique indicator to represent the casualty level of each urban zone in comparison with other zones, the casualty risk indicator ($R_{Casualty}$) is explained by Eq. (11) as an average of casualty states in three scenario time events (i).

$$R_{Casualty} = (1/3)\sum_{i=1}^{3}(0.66D + 0.33Se + 0.01Sl)_i \tag{11}$$

In this equation, importance weights for death (D), severe injury (Se) and slight injury (Sl) are determined based on engineering judgment about socio-economic effects of human casualties.

3.3.2.2. Density Indicator ($R_{Density}$)

This indicator is defined to consider the effect of evacuation and escape from buildings in time or just after the earthquake with respect to the hazard of building damages and fire spreading. Two parameters, that is, population density in buildings (Pd), and built floor area density in urban zone (*Bd*), are proposed to evaluate this indicator as follows:

$$Pd = {}^{Total\ Population}\!\Big/_{Built\ Floor\ Area}$$

$$Bd = {}^{Built\ Floor\ Area}\!\Big/_{Total\ Area} \tag{12}$$

Since each of these parameters aggravates the interruption effect of other one in case of population movement and evacuation, the multiplication of these two factors is recommended for estimation of density factor:

$$dF = Pd \times EXP(Bd) \tag{13}$$

In this equation, *dF* is density factor that represents the vulnerability in this field. *Pd* and *Bd* are population and built floor area densities, respectively. It is assumed that building density can exponentially increase the overall density factor, because, it implies the buildings height situation and existence of safe space among individual buildings, which are very important in evacuation condition. Finally, density risk indicator ($R_{Density}$), is estimated by multiplication of *dF* and its relevant hazard factor as:

$$R_{Density} = EH \times dF \tag{14}$$

where *EH* that is a significant threat for urban fabrics with high density is considered as the hazard factor. In other words, building damage and fire spreading hazards (*H*3 and *H*4 in Table (1)) are the most relevant hazards for parameters related to human behaviors. Accordingly, *EH* (Eq. (3)) is considered as the hazard factor for such parameters.

3.3.2.3. Unpreparedness Indicator ($R_{Unpreparedness}$)

Having sufficient information and ability to survive from the earthquake hazards are two important parameters to represent community preparedness. People information about earthquake preparedness and self-rescue is usually the same between residents in different parts of an urban area. Therefore, it is not included for estimation of preparedness level. However, age condition that represents the ability of evacuation and rescue in time or after the earthquake is not the same among urban zone's population, and can be used for this purpose. Based on JICA study [16], it is assumed that people with age between 5 and 65 have more ability for evacuation and self-rescue and the rest of people are considered as disaster weak population.

$$V_{Unpreparedness} = \\ \%\ of\ Population\,(65 < age\ or\ age < 5)$$

$$R_{Unpreparedness} = EH \times V_{Unpreparedness} \tag{15}$$

In Eq. (15), the risk of people unpreparedness ($R_{Unpreparedness}$) is estimated by multiplication of vulnerability ($V_{Unpreparedness}$) and hazard factor. The hazard factor for this indicator is supposed to be the same as *EH*, Eq. (3), as it is related to casualties and ability of people in evacuation and self-rescue.

3.3.3. Evaluation of Socio-economic Risk Index (R_{SE})

Human behavior, balance of production and demands for essential goods as well as political and economic regulations are some important issues in vulnerability assessment of socio-economic condition of urban areas. Main factors that affect social vulnerability are: lack of access to resources, limited access to political power and representation, social capital (social networks and connections), beliefs and customs, building stock and age, frail and physically limited individuals, type and density of infrastructure and lifelines [29-32]. In relevant literatures, variables such as age, gender, race, socio-economic status (income, political power and prestige), special needs population, employment, commercial and industrial development, education and social dependence were considered to have more impact on social vulnerability [29-36].

In this study, according to the previous variables and methods proposed in literatures, two indicators - household's economic condition and potential of social disruption due to earthquake consequences - are defined for assessment of socio-economic risk. It is assumed that, these two indicators can be used to characterize a broad dimension of social vulnerability, especially in urban zones whose available socio-economic data are not sufficient for detailed assessments. Accordingly, the socio-economic risk index ($R_{Socio\text{-}economic}$) is evaluated as:

$$R_{Socio-economic} = w_{Household\,E} \times R_{Household\,E} + \\ w_{Social\,disruption} \times R_{Social\,disruption} \tag{16}$$

where two relevant risk indicators - household economic condition and social disruption ($V7$-$V8$ in Table (2)) - are summed according to their weights (w).

3.3.3.1. Social Disruption Indicator ($R_{Social\ disruption}$)

Human behavior is an important cause of social disruption after an earthquake. The disruption is a result of people efforts to get their requirements and to preserve their lives and properties. Accordingly, four parameters -delinquency rate, social cohesion, level of education, and the economic importance of the zone- are considered as significant factors that may affect the social disruption.

Delinquency rate (*Dr*): This indicator is assessed based on information related to crimes for each locality that illustrate social degradation and quality of life of population [6]. Usually, the human safety is decreased after an earthquake in urban areas due to physical damages, social and economic disruptions and probable secondary hazards (e.g. fire). In this situation, most of the government and responsible organizations/agencies attention is paid to the rescue and relief activities. Therefore, the safety and security of damaged areas would be reduced and the rate of violence and delinquency can be increased. This may cause serious social and economic disruption that may result in future human casualty and physical loss, especially in zones that contain important economic or commercial places. Therefore, this parameter is considered to estimate the risk of security reduction after an earthquake.

Zone effect factor (*Zef*): Political activities are generally concentrated in the capital of each province (or state) and country, and disruption in that may affect whole people in and outside the zone [2]. In addition, urban zones differ in distribution of building's occupancy and human activities. Zones that contain important economic or governmental centers usually receive more population during the day from other zones. Consequently, the impacts of earthquake in these zones make considerable disruption in human life in and out of the zone. Here, the effect of this parameter in socio-economic risk is considered by the indicator of zone effect factor (*Zef*) as:

$$Zef = {(DSR \times Eo)}\Big/{(Eo + Ro)} \tag{17}$$

In this equation, *DSR* is the ratio of dynamic to static population. *Eo* is the floor area of important economic and governmental occupancies (such as, commercial, industrial and governmental occupancies), and *Ro* is the floor area of residential occupancy.

Social cohesion (*Sco*): Public participation in risk reduction and disaster management activities may significantly reduce the impacts of earthquake. Since the socio-economic condition and coping ability of people is not the same in all urban areas, the level of participation in such activities may differ zone by zone. The cohesion of population in an urban zone is a key parameter that can be used in assessment of willingness of residents to participate in group activities such as community based disaster management. It is assumed that, attendance of people in different social and religious community centers (e.g. mosques) can represent the level of social cohesion. Furthermore, social cohesion in traditional urban fabrics is higher than more developed zones. This parameter is estimated by Eq. (18).

$$Sco = (PA \times Mq)/(1 + dp) \tag{18}$$

where *Mq* is the factor associated to number of community centers (e.g. mosques), *PA* is the factor of people attendance in them, and *dp* is the development factor that usually has lower values in traditional urban fabrics and can be estimated indirectly by average age of the buildings.

Education (*Edu*): Lower education constrains the ability to understand warning information and access to recovery information [35]. Thus, the ratio of educated population is assumed as another vulnerability factor in this assessment.

Finally, the vulnerability and risk of social disruption is estimated by Eq. (19). Since the most important cause of human disruptions is physical damages beside secondary hazards, the hazard factor for this indicator is supposed to be the same as *EH*, Eq. (3).

$$\begin{aligned} V_{Social\,disruption} &= {Zef \times (1 + Dr)}\Big/{Sco \times (1 + Edu)} \\ R_{Social\,disruption} &= EH \times V_{Social\,disruption} \end{aligned} \tag{19}$$

In Eq. (19), *Zef* and *Dr* are zone effect factor and delinquency rate; and parameters *Sco* and *Edu* are social cohesion and education rate, respectively.

3.3.3.2. Household Economic Indicator ($R_{Household\ E}$)

Normally, wealth may enable communities to absorb impacts and recover from losses of disasters more quickly due to insurance, social safety networks, etc. [30]. The average income or economic state of households may indicate the resiliency and ability of people to handle their emergency requirements, especially in long term after the earthquake. Furthermore, usually one or two person in each household has individual income, so the household dimension is also an important factor that refers the economic dependency. The vulnerability and risk related to this indicator is estimated as:

$$V_{Household\ E} = {(HDm_{ave})}\Big/{(1 + Em_{ave} \times In_{ave})}$$
$$R_{Household\ E} = EH \times V_{Household\ E} \tag{20}$$

where HDm_{ave}, Em_{ave} and In_{ave}, are factors of average household dimension, average rate of employment and average income of employed people, respectively. Similar to social disruption risk, *EH* (Eq. (3)) is used as the hazard factor. Moreover, since in Eq. (20) the average value of household dimension is divided by average values of employment and income, this indicator can represent the potential of people assistance (as a big family) during the disaster situation.

3.4. Standardization of Indicator Values

The standardization procedure helps to make a better interpretation of the indicator values. In addition, it makes the differences to be consistent among component values in various urban zones. At the first step, the scale of the urban zone where the risk or response capacity indicators are being compared among them should be determined. In this study, it is assumed that, with the exception of “lifelines risk”, “transportation risk” and “response capacity” indicators, all other risk indicators can be estimated and standardized from neighborhood to whole city scales. However, indicators of lifeline, transportation and response capacity cannot be easily estimated in small zones such as blocks or neighborhoods, but they can be assessed in urban district scale. Finally, standardization of gross parameter values (in determined urban scale or “zone”) is done through Eq. (21). Consequently, indicators, sub-indicators and their components take values that are similar in magnitude.

$$x'_{ij} = \frac{x_{ij} - (\bar{x}_i - 2s_i)}{s_i} \tag{21}$$

In this equation, the mean $(\bar{x}_i)$ minus two standard deviations (s_i) method is used for normalizing each group of component values. x'_{ij} is the scaled value of x_{ij} (value of component *i* in urban zone *j*). This objective technique provides the consistency of values by making the mean of the scaled values equal to 2.0 and the standard deviation equal to 1.0. Therefore, this method directly evaluates each zone relative to all others (by involving the mean and standard deviation of all samples). This simple transformation will rarely produce negative values, and make results more understandable (usually the scaled values are between 0 and 4).

3.5. Total Relative Seismic Risk Index (RSRi)

When the risk index of physical (R_{PH}), human life (R_{HL}) and socio-economic (R_{SE}) are estimated at urban zones and gross values are normalized, the total relative seismic risk index (*RSRi*) is estimated as:

$$RSRi = \frac{w_{PH}\,R_{PH} + w_{HL}\,R_{HL} + w_{SE}\,R_{SE}}{1.0 + Ln\,(Rc)} \tag{22}$$

where w_{PH}, w_{HL}, and w_{SE} are importance weights associated to each of risk indicators, Table (2). In this equation, it is assumed that the response capacity index (*Rc*) reduces the risk by a natural logarithmic (*Ln*) function. Since in logarithmic function, the slope of the curve decreases as the value of response capacity (*Rc*) increases, it can represent the fact that an increase in *Rc* has more effect in reduction of overall risk index (*RSRi*) in urban zones having less capacity of response and recovery.

The application and effectiveness of the proposed model for estimating the risk of earthquake in Tehran Metropolitan area is presented and compared with study of JICA [16] in the following section.

4. Implementation of the Model for Tehran

Tehran is located in a seismic-prone zone, surrounded by some active faults and experienced several destructive earthquakes in its history, Figure (2). On the other hand, the vulnerability of the city to potential earthquake especially in old

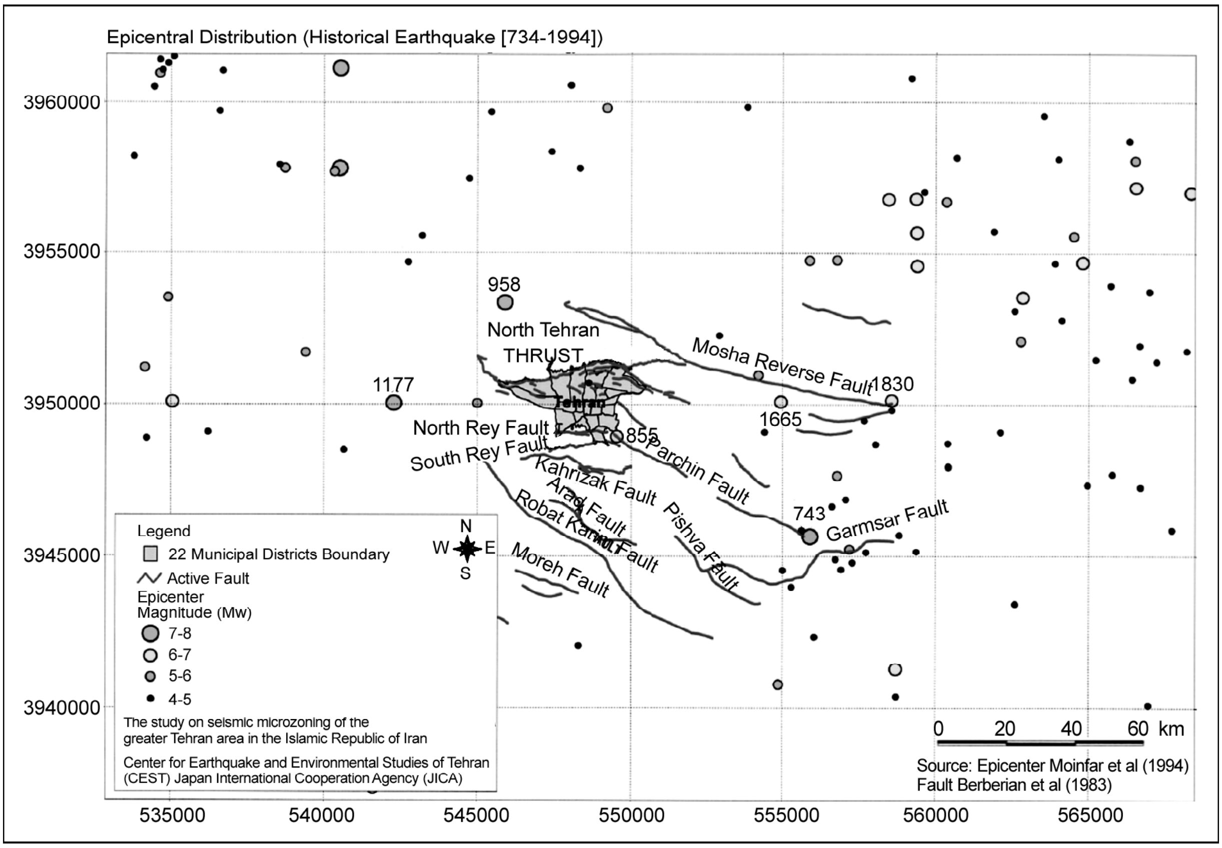


Figure 2. Main active faults and the location of historical earthquakes around Tehran [16].

urban fabric is significant. Weak buildings and structures, vulnerable lifelines, insufficient emergency response facilities, weakness of transportation systems and lack of sufficient evacuation places at some districts are the main parameters of earthquake vulnerability of the city. Several studies have been carried out by relevant authorities to estimate the risk of earthquake in this city. For example, JICA [16] and Ghayamghamian et al [19] studied the risk of earthquake in Tehran. Although they considered some aspects of physical vulnerability and risk, but many social and economic aspects of risk were not considered in their studies. Therefore, results are not applicable by city managers and decision makers for implementing risk mitigation activities based on priorities.

The proposed method in this paper has been applied for the assessment of seismic risk in Tehran to illustrate the impacts of different elements of hazard and vulnerability in total seismic risk. For this purpose, the Ray fault scenario, as the most destructive potential earthquake in Tehran [16], has been considered to assess the vulnerability and risk of earthquake. The required information for the model (hazard parameters, physical and socio-economic data) are gathered from Tehran Urban Planning and Research Center (TUPRC), Statistics Center of Iran (SCI) and JICA study [16], based on the 1996 Population and Housing census data. Figure (3) shows the distribution map of peak ground acceleration in different districts of the city.

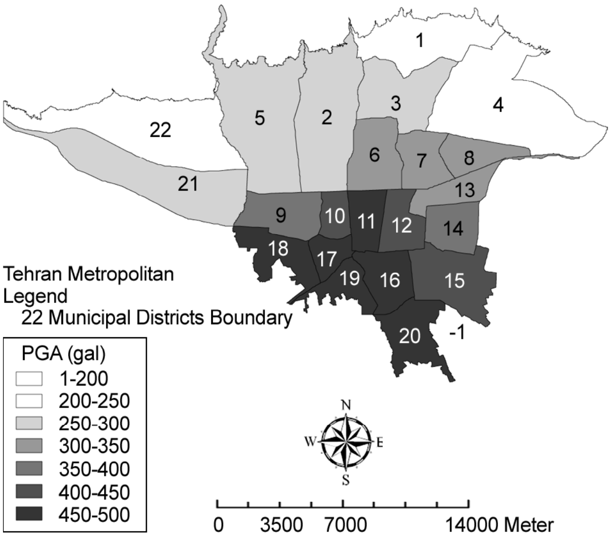


Figure 3. Peak ground acceleration distribution map for Ray fault scenario (adapted from JICA [16]).

4.1. Assessment of Physical Risk Index (R_{PH})

Physical risk index includes three indicators of building, lifeline and transportation risk. Figure (4) shows results of estimating these indicators as well as total physical risk index at different districts. As illustrated, building risk indicator at district 15 is higher than other districts due to having higher amount of vulnerable buildings and hazard (PGA). In addition, the lifeline and transportation indicator values are higher in zones with greater amount of hazard and vulnerability (such as districts 15, 16 and 20). As a result, the physical risk index in district 15 is relatively higher than other districts.

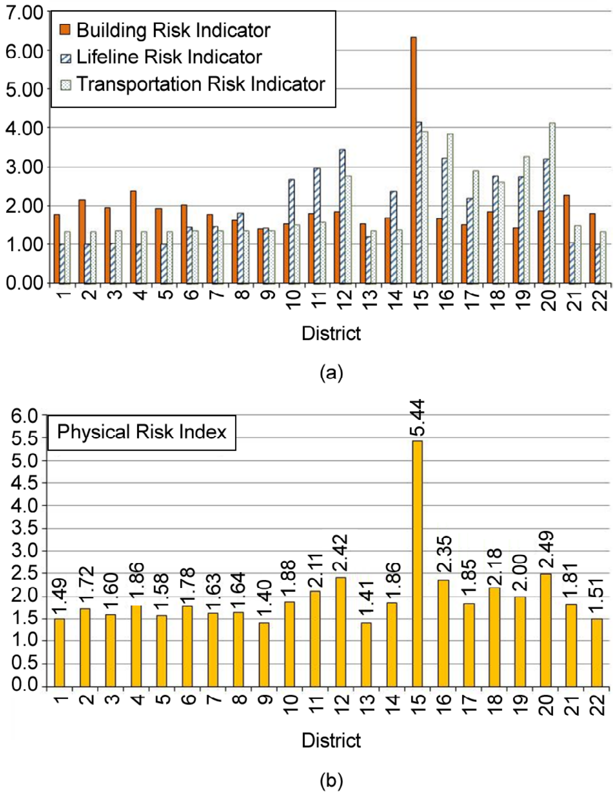


Figure 4. Normalized values of (a) Indicators of physical risk, and (b) Physical risk index, at each district.

Figure (5) represents the comparison of this study with JICA [16] for estimating the ratio of severely (or completely) damaged buildings. As depicted in this figure, ratios presented by JICA are more than our results; however, the overall trend is similar. This is due to employing different fragility curves for damage estimation. Moreover, we compute this ratio based on the building's floor area, whereas JICA estimated this value based on building's number.

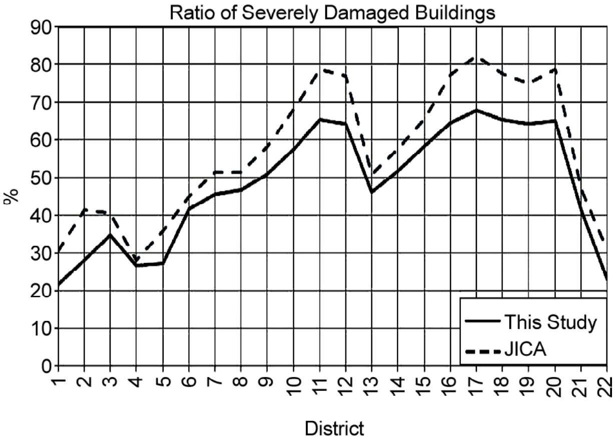


Figure 5. Comparison of results with JICA [16] for ratio of severely damaged buildings.

4.2. Assessment of Human Life Risk Index (R_{HL})

The human life risk index is composed of three indicators of casualty (due to building damage), density and unpreparedness risk. Figure (6) and (7) illustrates the results of the model in this part. In Figure (6a), results of casualty (number of the dead) estimation is compared with JICA [16] for night time earthquake scenario in conditions of full and no-rescue activities. As shown, results of this approach at different districts are higher than results reported by JICA. This is due to using different casualty rates, in addition to employing different collapse rates and local developed fragility curves. Also in our study, response capacity index is (*Rc*) considered separately and its effect is just included in the estimation of total relative risk index. Consequently, results of this study are more similar to JICA in case of no-rescue activities.

In Figure (6b), the distribution of gross values of casualty indicator (Eq. 12) at different time of the day and night are presented at different districts. As seen, in commercial centers (such as district 12), casualties in day time is higher than night time. This is due to distribution of population in day and night that has been considered in this study.

Figure (7a) shows the values of human life indicators. As illustrated, unpreparedness indicator in districts 12, 17, 18 and 20 are more than others; however, casualty and density indicators have their maximum value at district 15. According to Figure (7b), the human life risk index for district 15 is the highest, which is similar to physical risk index for this district.

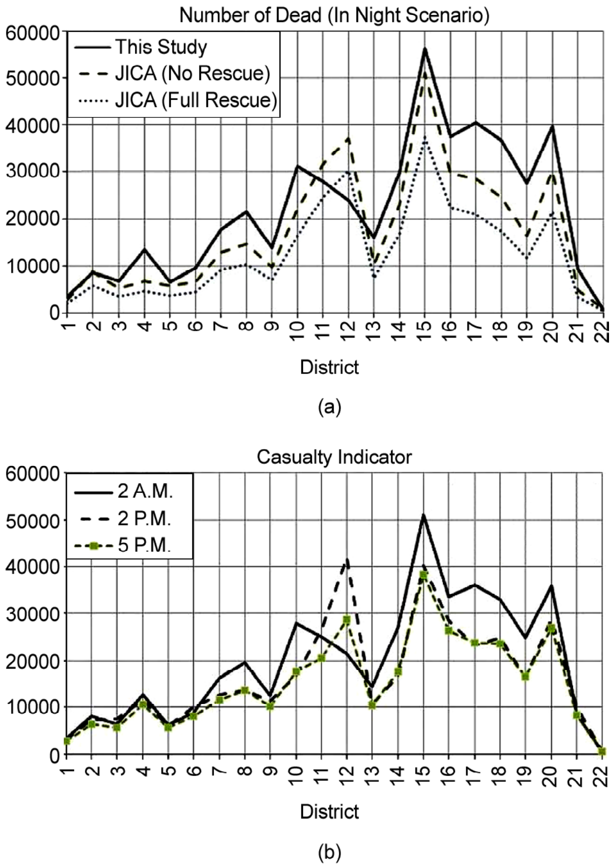


Figure 6. (a) Comparison of number of dead estimated by this model with JICA [16] for night-time scenario, (b) Gross values of casualty indicator in three scenario time.

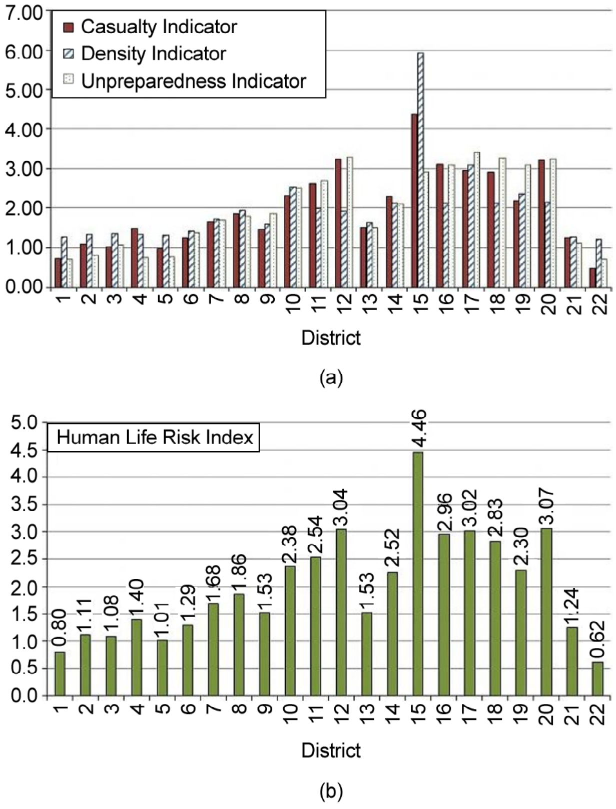


Figure 7. Normalized values of, (a) Indicators of human life risk, (b) Human life risk index.

4.3. Assessment of Socio-economic Risk Index (R_{SE})

This index composed of two indicators, social disruption, and household economic condition. These indicators are evaluated at Tehran districts and results are presented in Figure (8). At district 6, the dynamic over static population as well as delinquency rate are greater, whereas the social cohesion is relatively less than other districts. Therefore, it has the highest risk of social disruption. On the other hand, household economic risk indicator is higher in other districts such as 17, 18 and 19, in which the residents' incomes are lower, and usually the household dimension is more than others. According to the results, the socio-economic risk index in districts 6, 18 and 19 are greater than other districts.

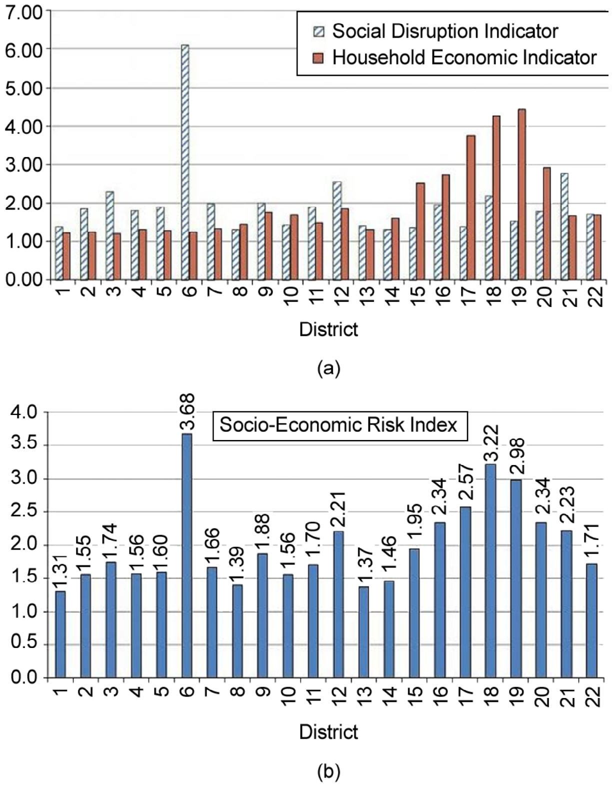
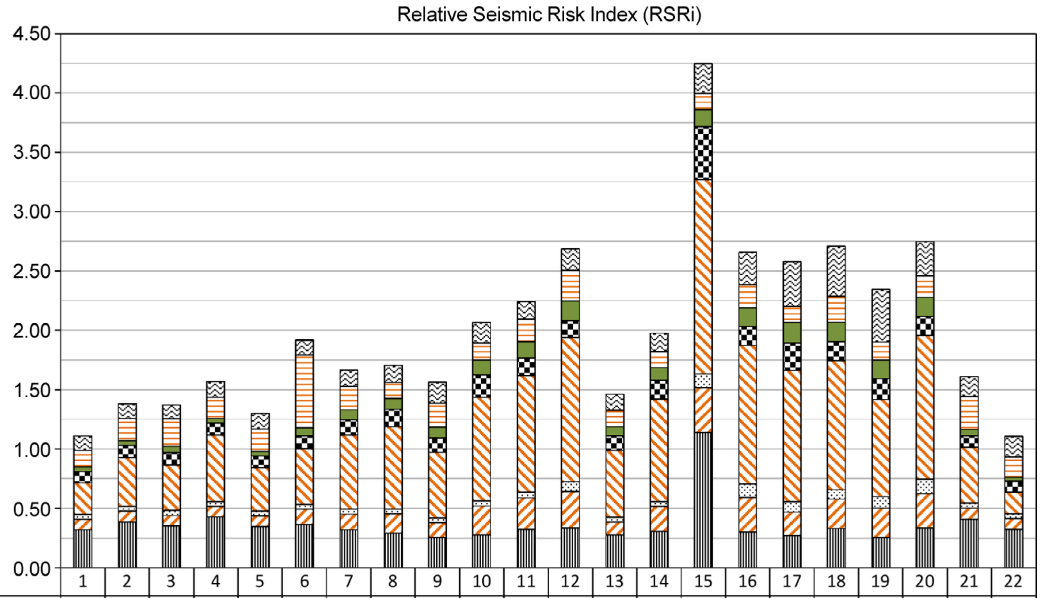


Figure 8. Normalized values of (a) Indicators of Socio-economic risk, (b) Socio-economic risk index.

4.4. Assessment of total Relative Seismic Risk Index (RSRi)

According to Eq. (22), the total relative risk index is evaluated by combination of risk and response capacity indicators. Figure (9) illustrates the amount of total relative risk index (*RSRi*) and contribution of each indicator in this value. Since the methodology for estimation of response capacity index is not final-



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
▨ Household E Indicator	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.15	0.18	0.17	0.15	0.19	0.13	0.16	0.25	0.27	0.37	0.43	0.44	0.29	0.17	0.17
⊟ Social Disruption Indicator	0.14	0.19	0.23	0.18	0.19	0.61	0.20	0.13	0.20	0.14	0.19	0.26	0.14	0.13	0.14	0.20	0.14	0.22	0.15	0.18	0.28	0.17
🟩 Unpreparedness Indicator	0.04	0.04	0.05	0.04	0.04	0.07	0.09	0.09	0.09	0.13	0.14	0.16	0.08	0.11	0.15	0.15	0.17	0.16	0.15	0.16	0.06	0.04
◙ Density Indicator	0.10	0.10	0.10	0.10	0.10	0.11	0.13	0.15	0.12	0.19	0.15	0.14	0.12	0.16	0.44	0.16	0.23	0.16	0.18	0.16	0.10	0.09
◪ Casualty Risk Indicator	0.27	0.41	0.38	0.56	0.37	0.47	0.62	0.69	0.55	0.87	0.98	1.21	0.56	0.86	1.64	1.17	1.11	1.09	0.82	1.21	0.47	0.18
⚄ Transportation Risk Indicator	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.08	0.04	0.04	0.12	0.12	0.09	0.08	0.10	0.12	0.04	0.04
◩ Lifeline Risk Indicator	0.09	0.09	0.09	0.09	0.09	0.13	0.13	0.16	0.13	0.24	0.27	0.31	0.11	0.21	0.37	0.29	0.20	0.25	0.25	0.29	0.09	0.09
▥ Building Risk Indicator	0.32	0.39	0.35	0.43	0.35	0.36	0.32	0.29	0.25	0.28	0.32	0.33	0.28	0.30	1.14	0.30	0.27	0.33	0.25	0.33	0.41	0.32

Figure 9. Normalized values of Relative Seismic Risk index (RSRi) in different districts and contribution of each indicator in total value.

ized at this stage, the value of this indicator in estimating the total risk index is considered equal to 1.0 for all districts. Figure (10), shows the average, maximum and minimum percentage of contribution to *RSRi* for each indicator. As illustrated, indicators of building and casualty risk, averagely compose more than 55% of *RSRi*. The lowest average contribution belongs to transportation risk and unpreparedness indicators having contribution less than 5%. However, results for maximum percentage of contribution show that contribution of all indicators is important and none of them is ignorable.

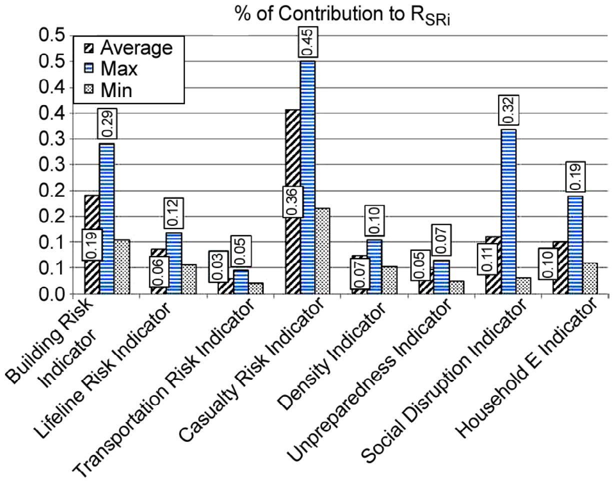


Figure 10. Average, maximum and minimum percent of indicator's contribution in RSRi.

Results of the proposed model can provide essential information about various aspects of seismic risk in urban zones. This is an appropriate tool for city managers and decision makers to perceive the contribution of each component in urban seismic risk, and consequently better understanding of mitigation priorities.

5. Discussion

Since earthquake disaster risk cannot be measured directly, there is no determinate way to validate the risk estimation methodologies [2]. However, such methodologies can be verified to some degree by another indeterminate means. For example, some features of the proposed model that helps for validation are:

- ❖ The proposed model takes into account various aspects of seismic hazards and vulnerability (physical, human life, socio-economic) of urban fabrics. Furthermore, the response capacity aspects are considered for risk estimation. Therefore, it can be considered as a comprehensive model in this field.

- Indicators are selected in a way to represent their relevant concept. Besides, effects of each indicator in increasing or decreasing the risk are considered.
- Importance weights associated to each indicator and index are determined using the opinions of relevant experts. Therefore, it includes the experiences gained in previous events as well as the local characteristics of the studied region.
- The model can be implemented in urban fabrics affected by seismic event in the past and results can be verified (if required data are available) or compared with other methodologies. For example, in this study, some results are compared with JICA study for Tehran [16].

Sensitivity analysis should also be performed to determine the robustness of the model according to uncertainties. Five possible origins of uncertainty that can be introduced are: indicator definitions, indicator selection, weights, scaling function and input data. Indicators should be defined and selected in order to appropriately characterize the proposed concept for risk estimation. If this criterion is respected, uncertainties of this part make no problem for the model. In other words, changing the indicator set may influence the measuring concept, so relative values of different urban zones can be changed as well. Similarly, changing values of importance weights influences final results. Like indicator set, weight values help to define the risk concept, and changing the weights affects the measuring concept, and obviously the urban zone rankings in new concept may differ from those associated with the original concept. However, it should be assessed that results would not vary too much with minor changes in value of weights.

Since the proposed methodology measures only relative values, sensitivity of relative values (and not the absolute ones) should be surveyed. Therefore, it does not make any difference if by employing some different scaling schemes, the values of zonal risk indicators change. This is because changes for the values of risk indicators are sought in the relative sense. Even if ratios of the scaled values of two urban zones were not identical across different scaling techniques, the ranking score for the risk values would not change among urban zones.

However, the verification of the reasonableness for the results and effects of data uncertainty should be surveyed according to existing or actual data upon availability. More detailed discussion on the results regarding the proposed model will be presented in our future research reports.

6. Conclusion

In this study, a new simplified methodology is proposed for assessment of vulnerability and seismic risk in urban fabrics based on physical, human life and socio-economic parameters. In addition, response capacity and recovery capability aspects are also considered in the risk estimation procedure. Consequently, the proposed methodology helps in developing a systematic procedure in assessing the urban risk by means of:

- Presenting a comprehensive methodology: Since the physical, human life and socio-economic parameters that significantly contribute to seismic risk as well as response capacity aspects are considered, results of the model can comprehensively illustrate the seismic risk of urban fabrics.
- Estimation of relative risk: The proposed method estimates the relative seismic risk instead of absolute risk in order to interpret the risk differences between urban zones. Therefore, it is convenient to utilize simple and indirect methods to evaluate the risk and vulnerability indicators with fewer amounts of required data.
- Definition of hazard factors: According to the fact that each of earthquake related hazards (ground motion, ground failure and secondary hazards) has different effects on urban areas, different hazard factors are used for better interpretation of hazard and vulnerability combination. In addition, it can reduce the risk estimation uncertainties in this field.
- Local characteristics of the model: Since the methodology is proposed mainly for seismic risk estimation in Iran, an effort is made to quantify the parameters of the model by means of local studies. For example, an applicable relationship is proposed for estimating the collapse probability for various building types according to the database created after the 2003 Bam earthquake. Furthermore, opinions of Iranian experts are used for selecting indicators and determining their

relevant importance weights through AHP method.

The proposed model is applied for assessment of seismic risk in Tehran. As a result, the estimated values of RSRi and its sub-indicators are reported at each district of the city. Results show that relative values of physical, human life and overall risk indices in district 15 are significantly greater than other districts. However, in socio-economic aspects, district 6 has the highest rank of risk. According to the distribution of earthquake hazard, vulnerable buildings and population density, the results have a good compatibility with the expected condition of risk in different districts of Tehran. In addition, the contribution amount of each indicator in *RSRi* is reported for each district. This output can be used by managers as an appropriate tool to understand priority decisions for risk mitigation. Finally, in some cases, the outcomes are compared by results of JICA study [16] for Tehran, and a good agreement between them is discovered. Altogether, the proposed approach in this study is a model expressed and formulated in a realistic possible manner at present. However, the model can be adjusted according to some modifications based on future studies and findings.

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