A New Method for Assessing the Seismic Risk Index of Urban Fabrics

M. Hajibabaee[1], K. Amini Hosseini[2] & M.R. Ghayamghamian[3]
1-Ph.D. Student, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran
2-Assistant Professor, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran
3-Associate Professor, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran

SUMMARY
The exponential increase in the world's population and the irregular growth of big cities, which is characterized by the improper occupancy of the land, largely contributes to the vulnerability of urban fabrics to seismic events. In order to effectively reduce the vulnerability of urban fabrics to potential earthquakes, it is necessary to make a comprehensive assessment of the existing risk 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.
In this paper, a holistic seismic risk assessment approach is proposed for Tehran city. For this purpose, physical and socio-economic parameters that mostly contribute to seismic risk estimation of urban areas are introduced. The proposed approach estimates the risk indicator associated to each parameter according to its high related hazards. Finally, the total risk index is evaluated via the weighted combination of risk indicators.

Keywords: Seismic risk, mitigation, urban fabrics, Tehran City

1. INTRODUCTION

Seismic risk is a non-linear combination of existing earthquake hazard and the vulnerability state of exposed elements of the city. There have been many attempts for developing vulnerability assessment methodologies and use it in earthquake risk assessment by considering various aspects of vulnerability, such as, physical, social, economic and other parameters (e.g. Davidson and Shah 1997). Moreover, the developed methodologies vary in scale, such as local, regional, national and international levels. Examples of risk assessment methods incorporated with vulnerability analysis at different levels can be found in Radius (1999), FEMA-NIBS (1999), Cardona (2001), Kundak (2004), Birkmann (2007), Amini Hosseini et al. (2009), Duzgun et al. (2011). Among these examples, Earthquake Disaster Risk Index (EDRI) presented by Davidson and Shah (1997) is one of the pioneer models, which provide a multidisciplinary approach by considering several aspects of risk and vulnerability. As EDRI has been developed for comparisons of relative risk of different cities, it can not compare the risk of urban fabrics within a city, which is required for developing effective disaster risk reduction plans. In Radius (1999) project, earthquake risk for different cities selected from Asia, Europe, the Middle East, Africa, and Latin America is assessed considering mainly physical urban environment, such as buildings, infrastructures, etc. HAZUS, which was developed by FEMA-NIBS(1999), considers socio-economic aspects of urban earthquake risk as well as buildings, lifelines, transportation and infrastructure. Although HAZUS methodology is one of the most complicated urban earthquake risk assessment approach, its application is limited as it is designed for the United State physical and social conditions. Recognizing these facts, several initiatives in Europe have been started to develop earthquake risk assessment and loss estimation methodologies across the Euro-Mediterranean region. The final products of their studies are usually software packages for assessing the seismic risk and earthquake losses.

Cardona (2001) developed a model for the seismic risk analysis of urban centers from a holistic view, which considers both 'hard' and 'soft' risk variables. This model takes into account physical risk, exposure and socio-economic characteristics of the different units of the city and their disaster coping capacity or degree of resilience. This helps to identify the critical zones of a city and their vulnerability from the multidisciplinary point of view. Amini Hosseini et al. (2009) evaluated the seismic vulnerability of Tehran city by considering some of physical and socio-economical parameters. They compared the results with existing plans and programs for rehabilitation of the old urban fabrics in Tehran city prepared based on the regulations of ministry of Housing and Urban Development of Iran. The results show that the plans which are prepared only based on physical vulnerability can not properly identify the priorities for rehabilitation of urban fabrics and it is necessary to consider the role of earthquake related parameters as well as socio-economic conditions for improvement of vulnerable areas. Duzgun et al. (2011) proposed an integrated urban earthquake vulnerability assessment framework. They consider vulnerability of urban environment in a holistic viewpoint and perform the vulnerability assessment in the neighborhood scale. The methodology integrates socio-economic, structural, coastal parameters as well as ground condition, vulnerabilities and accessibility to critical services. The proposed approach is implemented for Eskisehir, which is one of the metropolitans of Turkey.

In this paper, a holistic seismic risk assessment approach is proposed for urban areas. For this purpose, physical and socio-economic parameters that mostly contribute to seismic risk estimation of urban environment are categorized. The proposed approach estimates the risk indicator associated to each parameter through the multiplication of vulnerability factor by the hazard factor. The hazard factor estimated separately for each type of vulnerability factor. Finally, the total relative risk index is evaluated using the weighted combination of risk indicators. As the method estimates the relative seismic risk, simple and indirect parameters were used to estimate the risk indicators. Therefore, the proposed methodology can be used for cites like Tehran, where the required data are usually missing or inadequate to make the decision-makers able for prioritization their limited resources in risk reduction programs.

2. SEISMIC RISK ASSESSMENT IN TEHRAN CITY

Tehran city is located in a seismic prone zone, surrounded by some active faults and experienced several destructive earthquakes in its history (Fig 1.). Based on the probabilistic and deterministic evaluations, seismologists believe that a strong earthquake may occur in or around the city in near future. The vulnerability of the structures, infrastructures and socio-economic aspect of the city is considerable, especially in old urban fabrics. Weak buildings and structures, vulnerable lifelines, insufficient emergency infrastructures and transportation systems, lack of sufficient evacuation places and roads at some districts are some of the main parameters of earthquake vulnerability of the city.

Furthermore, there is still no integrated plan for allocation of budget based on vulnerability and hazard parameters for rehabilitation of vulnerable urban fabrics. Therefore developing a practical method for is essential for prioritizing the risk reduction activities effectively. For this purpose, several activities have been carried out by relevant authorities. For example, TDMMO and JICA (2004) and Ghayamghamian et al. (2011) were studied the seismic risk of earthquake in Tehran city. Although they consider some aspects of vulnerability and risk but many social and economic aspects of risk were not involved in their studies. So the results are not sufficient to reduce the vulnerability of the city effectively.

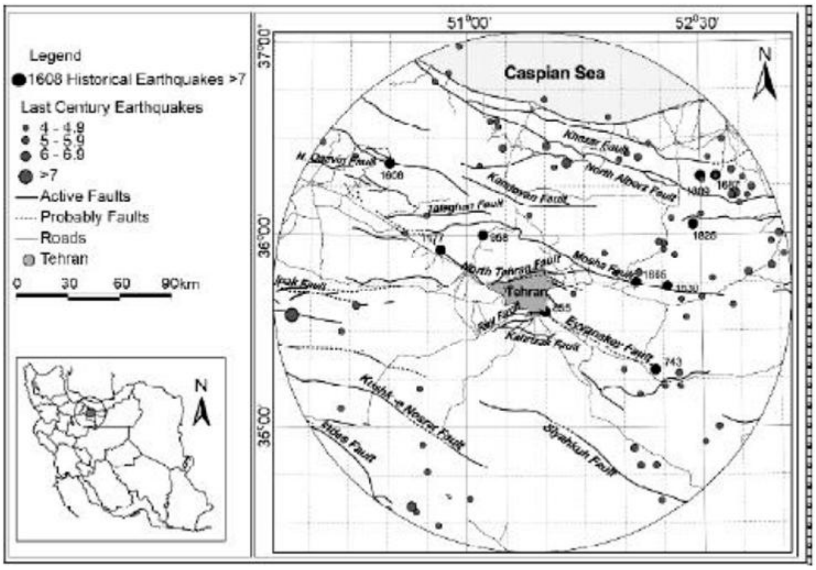

Figure 1. Main faults around Tehran and the location of historical and recent earthquakes around the city in 150 km radius (Amini Hosseini and Hosseini, 2007).

3. THE PROPOSED SEISMIC RISK ASSESSMENT APPROACH

In order to perform a holistic assessment of the earthquake risk in urban areas, besides having sufficient information about the existing earthquake hazards at each zone, it is necessary to assess the vulnerability of all different exposed elements of the area against those hazards. When an earthquake occurs, beside ground motion, some other hazards like landslide, subsidence, liquefaction, surface fault rupture and secondary hazards (like fire following and inundation) are probable to happen. Each of these hazards has different effects on the consequence of the earthquake in an urban area. Therefore it is necessary to use different combination of these hazards for each vulnerable aspect at urban area in risk assessment. For example, liquefaction and subsidence have more effects on disruption of utility lifeline networks and transportation systems, but they may not be so important in building damage or casualties.

Here, an approach is proposed to estimate the relative seismic risk for urban areas in the urban district scale. In the first step, the physical and socio-economic parameters that mostly contribute to seismic risk estimation of urban environment are introduced and classified into three types of physical vulnerability, life safety vulnerability and socio-economic vulnerability. Furthermore the response capacity indicators that help to reduce the disaster consequences are presented in section 3.1. In section 3.2, the method for combination of most important related hazards for each type of vulnerability aspect is presented. The procedure to estimate the risk indicator associated to each parameter according to its high related hazards is presented in section 3.3. Also the mathematical model to evaluate the total relative risk indicator via the weighted combination of risk indicators is presented in that section.

Figure 2, shows the procedure of the proposed approach to estimate the total seismic risk index in urban areas. As illustrated in this figure, in the first step by using the existing data and information of probable ground motion, ground failure and the potential of secondary hazards, the related hazard factor (Rhaz) for each type of vulnerability is computed. Then, by using the results of the vulnerability assessment, risk indexes can be estimated through the multiplication of the hazard factor by vulnerability factor. The response capacity factor is also estimated by the weighted combination of its components. Once the total relative risk is estimated through the model, managers and policy makers can understand the influence of each parameter to reduce the seismic risk. After taking some mitigation strategies, the new value for vulnerability, response capacity, hazard factors and total risk can be assessed in order to estimate the effectiveness of employed activities and programs.

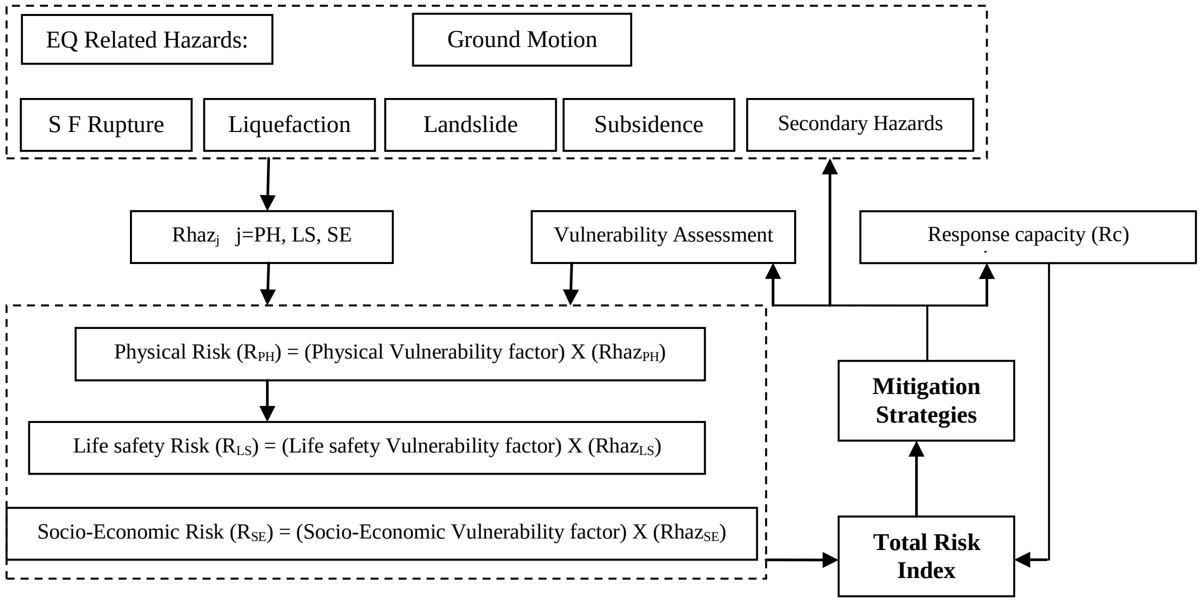

Figure 2. The procedure of the proposed approach to estimate the total seismic risk index

3.1. The Seismic Risk and Response capacity Indicators

After framework of the approach was created, some simple, measurable and scalar indicators were selected to represent each of the main factors in the framework. Since there are no indicators that can be proven to be the "correct" ones, it was helpful to consider the criteria that an ideal indicator would satisfy, and then judge the possible indicators on the basis of their ability to these criteria (Davidson 1997). When the seismic risk is compared among local areas (urban districts), it is convenient to use simple and indirect methods to choose and quantify the parameters for relative seismic risk estimation.
According to consequences of earthquake in an urban area, the vulnerability components of an urban area can be considered in three main categories. In the first category, the vulnerability of physical elements of the city (Physical Vulnerability) is determined using common simple methods. In the second category, the vulnerability of life safety of people (Life Safety Vulnerability) is determined through its sub-components. Finally, the third category determines the vulnerability of the city to cope with socio-economic disruptions (Socio-Economic Vulnerability) caused by earthquake. Unlike first and second category, the last category is not dependent to the hazard of earthquake. The three main categories of vulnerability and each sub-component are illustrated in Table 1.

Table 1. The three main categories of vulnerability Indicators

Main Category (Index)		Sub-components (Indicators)
Physical Vulnerability (V_{PH})		X1: Building's vulnerability
		X2: Utility lifeline's Vulnerability
		X3: Transportation Vulnerability
Life safety Vulnerability (V_{LS})		X1: Building's vulnerability
		X4: Density (Population and Buildings)
		X5: Preparedness (of people)
Socio-Economic Vulnerability (V_{SE})	Social Vulnerability (V_S)	X6: Development Index
		X4: Density
		X7: Delinquency
	Economic Vulnerability (V_E)	X8: Household economic power
		X9: District economic power
		X10: District Effect Factor
		X6: Development Index

3.1.1. Physical vulnerability

The seismic vulnerability of physical elements of an urban area like buildings, utility lifelines networks and transportation networks are considered in this category. Damage to the physical part of an urban area will result to large amount of direct economic loss. Also it is the main cause of casualty and disruption. Indicators of building vulnerability, utility lifeline's vulnerability, transportation vulnerability are used to estimate the vulnerability of physical part. Fragility curves can be used to simply estimate these indicators.

3.1.2. Life Safety Vulnerability

Usually the main goal of reducing the seismic risk in urban centers is to reduce casualties. Here the vulnerability of this part is estimated using three indicators. Building vulnerability in various land-uses is the main indicator. Also the density of the people and buildings and the preparedness of people are very important in loss of life soon after the disaster.

3.1.3. Socio-Economic Vulnerability

After the earthquake disaster, the disruption of social and economical activities may cause damaging effects on social and economic aspects of the city. Controlling the safety of the city, adjusting production and demand of essential materials, political and economical effects of the earthquake in and out of the area are the consequences of the earthquake in socio-economic part. Here, we consider six parameters to capture all aspect of disruptions as: development condition of district in social and economic aspect, density of people and buildings, rate of delinquency, household and district economic power and district effect factors (social, political and economic effect of each district on other districts).

3.1.4. Response capacity

Response capacity of a city involves human and physical resources and equipments that would help to reduce the consequences of an earthquake in the city. Here the indicator of response capacity is determined through its sub-components that illustrated in Table 2.

Table 2. Response capacity Indicators

Main Category (Index)	Sub-components (Indicators)
Response capacity (Rc)	C1: Management Index
	C2: Resource Index
	C3: Evacuation Capacity Index
	C4: Accessibility Index

3.1.5 Estimation of main indexes

In order to evaluate four main indexes, simple additive weighting (SAW) method is used, where the sub-component indexes are given weights according to their importance. The overall index (*Ij*) for each of main indexes is computed using Equation (3.1).

$$I_j = \sum_{k=1}^{k=n} w_{k_j} \times indicator\ \ value(k_j) \qquad j = V_{PH}, V_{LS}, V_{SE}, Rc \qquad (3.1)$$

$$Note: \sum_{k=1}^{n} w_{k_j} = 1$$

Where, *Ij* is the indicator for physical vulnerability, life safety vulnerability, socio-economic vulnerability and response capacity. Parameter n is the number of sub-components of each main index and w_k is the importance weight of each indicator. The weights in the proposed approach were determined by expert opinion through subjective assessment, using AHP method. Note that, the sum of weights in each weighting combinations is equal to 1.

The indicator value (k_j) is quantified for each sub-component (*X1*:*10* and *C1*:*4*) through a simple procedure by using available data in the city.

To quantify each indicator, at first the value of its components is scaled, then the components are combined according to their weights. The scaling procedure helps to make the interpretation of the indicator values and the local area differences consistent among indicators. This is done by transforming the values so that all indicators take values that are similar in magnitude and unit. The scaling method used in this approach is to scale the values with respect to the mean minus two standard deviations of the sample of local areas. The value x_{ij} for each indicator *i* and local area *j* should be scaled using the equation (3.2) if the indicator is directly related to earthquake disaster risk.

$$x'_{ij} = \frac{x_{ij} - (\bar{x}_i - 2s_i)}{s_i} \qquad (3.2)$$

Otherwise, using equation (3.3), if the indicator is inversely-related to earthquake disaster risk:

$$x'_{ij} = \frac{-x_{ij} + (\bar{x}_i + 2s_i)}{s_i} \qquad (3.3)$$

In these equations, x'_{ij} is the scaled value of x_{ij} that indicates the value of indicator *i* and local area *j*. Parameters s_i and $\bar{x}_i$ is the standard deviation and mean value of indicator *i*.

3.2. Hazard Factors

Except parameters of ground motion (PGA, PGV, Intensity), seven types of hazards that are probable to be caused by earthquake were considered in assessing the hazard factors through six hazard categories, as listed in Table 3. Indicators of surface fault rupture, liquefaction and subsidence are considered in one group due to their same effects on structural damage. Each of these hazards has different effects on the consequence of the earthquake in an urban area. So it is better to use different combinations of these hazards for each vulnerable aspect in risk estimation at urban fabrics. For example, liquefaction and subsidence have more effect on disruption to utility lifeline networks and transportation systems but less effect on building damage or casualties.

Table 3. Hazard Factors components

	Sub – Index	Sub-components (Indicators)
EQ Related Hazards	H1	Ground motion (PGV)
	H2	Surface fault rupture
		Liquefaction
		Subsidence
	H3	Landslide
	H4	Fire
	H5	Inundation
	H6	Hazardous Materials

The factor of hazard for each type of vulnerability is determined via the weighted combination of hazards, but the weights are different for each factor. The hazard factor (Rhaz) for each type of vulnerability (Physical, Life Safety and Socio-economic vulnerabilities) is estimated through equation (3.4) as:

$$Rhaz_j = \sum_{i=1}^{6} w_i H_i \qquad j = PH, LS, SE \qquad (3.4)$$

The weights in the proposed approach were determined using expert opinion by AHP method. Note that, the sum of weights in weighting combination is equal to 1.

3.3. Total Relative Seismic Risk Index

The risk is a combination of hazard and vulnerability factors (Risk = Hazard x Vulnerability). The amount of risk index for each type of vulnerability is estimated through the following equations:

$$R_{PH} = H_{PH} \times V_{PH}$$
$$R_{LS} = H_{LS} \times V_{LS} \qquad (3.5)$$
$$R_{SE} = H_{SE} \times V_{SE}$$

Where, R_{PH}, R_{LS}, R_{SE} are the physical, life safety and socio-economic risk indexes respectively. The following equation are used to combine the risk indexes into the total risk index:

$$SRI = e^{-Rc}(w_{PH}R_{PH} + w_{LS}R_{LS} + w_{SE}R_{SE}) \qquad (3.6)$$

In this equation, it is assumed that the response capacity factor can exponentially reduce the risk of earthquake in urban fabrics, since an increase in capacity of response has more effect on reduction of the seismic risk. However other three indexes of risk are combined linearly by their importance weight (*w*). The weights in the proposed approach were determined by expert opinion using AHP method and the sum of weights is equal to 1.

4. CONCLUSION

The risk of earthquake in urban areas is a combination of earthquake related hazards and vulnerability level of urban components. In cites like Tehran, the required data are usually missing or inadequate to make the comprehensive assessment of seismic risk and inform decision-makers about prioritization their limited resources in risk reduction programs. Therefore, in this study, a new methodology was proposed to simplify the assessment of seismic risk in urban fabrics. First, a simple and measurable set of parameters were proposed to assess the vulnerability of urban areas in physical, life safety and socio-economical aspects. Then the seismic risk was estimated through combination of earthquake hazard factors and the assessed vulnerabilities.

According to the fact, that each of earthquake related hazards (ground motion, ground failure and secondary hazards) has different effects on the consequence of an earthquake in the urban area, it is necessary to use different combinations of these hazards for each vulnerable aspect in urban area for estimating seismic risk. Therefore, using expert opinions, a weighted combination of these hazards were proposed to estimate the hazard factors. As a result of this approach, a separate earthquake hazard factor (Rhaz) was determined for each category of vulnerability parameters. This procedure will reduce the risk estimation uncertainties in the procedure of combining hazard and vulnerability.

In the proposed methodology, the seismic risk was relatively estimated between urban areas in district scale. The relative risk estimation was used to compare the amount of seismic risk between areas instead of computing absolute seismic risk or amount of losses and casualties. Furthermore, it has advantage of using simple and indirect methods to evaluate the parameters of hazard and vulnerability, since urban characteristics and uncertainties are usually same in areas that consider to be compared. The model application and effectiveness for comparing the risk of earthquake between different districts in Tehran city will be presented in future papers.

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