Earthquake Vulnerability Assessment in urban areas using MCDM

Case study: The central part of 6th district of Tehran Municipality

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Abstract: The earthquake vulnerability is one of the main problems of Iranian cities. This problem is going to be considered because of neglecting updated techniques for vulnerability assessment. There are numerous analytical techniques, in which some of them are useful to reach the responsive solution in software aspects. It is assumed that using techniques such as Analytic Hierarchy Process (AHP) supplementary by Fuzzy Logic can be helpful in this regard. This research is going to experience this technique in a case study in the 6th district of Tehran municipality. AHP is used in order to achieve the importance factor for each criterion which involved in the earthquake vulnerability and the Fuzzy Logic is used to normalize them. At last the consequent vulnerability function due to the criteria has been acquired. As a result, the purposed vulnerability model and map can become a significant software tool for confronting crises resulting from future earthquakes incidences and reduce the probable damages and vulnerabilities.

1. INTRODUCTION

Many of cities are located in areas that are endangered by natural disasters, such as earthquake, flooding, cyclones/hurricanes, landslides, volcanic eruptions, subsidence etc. It is estimated that over 95 percent of all deaths caused by disasters occur in developing countries and losses due to natural disasters are 20 times greater (as percent of GDP) in developing countries than in industrial countries ([Kreimer, et al., 2003](#)). Two million people will die in earthquakes in the twenty-first century assuming no increase in the average annual rate of deaths from the twentieth century ([Nicholas, 2005](#)). While natural disasters cannot be avoided, there are ways to improve safety, minimize loss and injury, and increase public awareness of the risk involved. One of the most effective ways to lessen the impact of natural disasters on people and property is through risk assessment and mitigation ([Tantala, et al., 2008](#)). Earthquakes cause huge loss of lives and infrastructure every year in Iran. Many settlement areas (urban & rural) as well as Tehran, the capital city of Iran are located in hazardous area ([Sharifikia, 2011](#)). The disastrous impact of earthquakes has been starkly illustrated in Bam-2003, Ardabil-1998, Ghaenat-1996, Manjil-1990, where thousands of people lost their lives ([Sharifikia, 2007](#)). Vulnerability is a new field and analytical tool in the study of urban safety. Analysis and assessment of vulnerability provide a new basis for urban planning ([Chunliang, et al., 2011](#)).

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Earthquake vulnerability can be assessed and predicted through scientific analysis of earthquake risk map, and thus damages can be decreased through prevention effort ([Sharifikia, 2011](#)). For a vulnerability assessment, the goal is obtain a detailed map of distribution of building damage expected for occurrence of a scenario earthquake ([Fah, et al., 2001](#)). AHP, as a multiple criteria decision making (MCDM) method, can be used to evaluate and access the vulnerability of earthquake. In the last 20 years, AHP has been used in almost all the applications related to multiple criteria decision-making ([Vargas, 1990](#); [Vaidya, 2006](#))

In this paper, an AHP-based model has been developed for assessing the probable earthquake vulnerability in the studied area, which is located in the central part of 6th district of Tehran municipality.

2. THEORETICAL BASIS OF ANALYTIC HIERARCHY PROCESS

The AHP is a method proposed by Saaty ([Saaty, 1980, 2008b](#)). AHP is a well known technique that decomposes a decision making problem into several levels in such a way that they form a hierarchy with unidirectional hierarchical relationship between levels. The AHP uses pair wise comparison to allocate weights to the elements of each level in model, measuring their relative importance by using Saaty's 1 to 9 scales, and finally calculates global weights for assessment at the bottom level. The method also calculates a consistency ratio (CR) to verify the coherence of the judgments, which must be about 0.1 or less to be accepted. Mathematical foundations of AHP can be found in Saaty ([1994,1996](#)).

3. AHP-BASED METHODOLOGY FOR THE EARTHQUAKE VULNERABILITY ASSESSMENT

This study represents a conceptual framework for assessing the potential earthquake consequences to estimate the scale and extent of damage and disruption that may result from potential earthquake in the studied area. This model uses AHP, Fuzzy Logic and Probability Function to estimate the probable vulnerability. AHP is used to calculate the importance ratio for each criterion. In continues, the criteria have been converted from classic state to the fuzzy and unscaled condition using the fuzzy logic and the linear threshold function. Finally, the probability function of the vulnerability has been defined base on the criteria in the GIS environment and then the vulnerability values have been calculated for each parcel. A conceptual view of how the purposed model works is shown in the Figure1.

Figure 1. Proposed conceptual framework for assessing the earthquake vulnerability

3.1 Selection criteria

In order to develop an AHP model, a thorough literature review and informal discussions with the officials of the municipality, academics and experts working in the field of earthquake vulnerability were carried out and appropriate criteria for assessment have been extracted and classified (Table1).

Table 1. Description of selection criteria

Row	Criteria	Description and Explanation	Reference	Source
1	Land Use	Land use play a key role in earthquake vulnerability due to its occupy class and its relative dangerous. The vulnerable ratio is difference from one land use to the others. For example, green spaces are less vulnerable than residential lands.	Sengezer & Ercan, 2005; Torabi, 2010	Tehran Municipality
2	Plot Area	Area has an inverse correlation with the earthquake vulnerability. Large lands are less vulnerable than small lands.	Abdollahi, 2004	NICO (National Iranian Cartography Organization)
3	Geometric Shape	The regular shapes have less vulnerability and vice versa.	Hamidi, 1992	NICO (National Iranian Cartography Organization)
4	Parcel location in the block	According to earthquakes damage statistics in Iran, It is believed that parcels which are located in the middle of block have less vulnerability and them which are located in the border, have more vulnerability. It is because of surrounding by other building and their structures that help these building to be more resistant.	Ahadzadeh Roshti, 2010	NICO (National Iranian Cartography Organization)
5	Population	However, it has not a straight relationship to the damages, it is an important criterion	Fakhim, 2006	Tehran Municipality

	Density	in the casualties due to earthquake.		
6	Type of Structure	The Skeleton type of building has a drastic role in the damages. For example, wooden skeleton is more vulnerable than others type like metal and concrete floors.	Hatami Nejad et al, 2009	Tehran Municipality
7	Quality of Construction	It is distinguished that buildings with better quality (new technology in construction) have less vulnerability.	Ahadzadeh Roshti, 2010	Tehran Municipality
8	Building Age	As the building age arises, the probability of its vulnerability goes up.	Hoseini, 2003	Tehran Municipality
9	Number of Stories	It has a straight relationship with the earthquake vulnerability. Tall building are more vulnerable than short ones.	Ahadzadeh Roshti, 2010	Tehran Municipality
10	Occupancy Ratio	When in a parcel the occupancy ratio raises, it means that the open space in comparison to the mass space decreases and it can increase the vulnerability.	Hamidi, 1992	NICO (National Iranian Cartography Organization)
11	Density	It is the rate of construction in relation with plot area that is the multiple of numbers of stories and occupancy ratio.	Habibi et al, 2007	Tehran Municipality
12	Road width	It is important for the access to safe places and rescue vehicles transportation.	Fakhim, 2006	NICO (National Iranian Cartography Organization)
13	Access to Open Spaces	Open spaces as safe places during the earthquake and after that has an important role in lowering the vulnerability and casualties.	Habib, 1992	Tehran Municipality
14	Access to Rescue Centers	Access to rescue centers and other emergency centers during and after earthquake has a significant role in reduction the fatalities.	Habibi et al, 2007	Tehran Municipality
15	Access to Fire Stations	As it is probable to accrue fire after the earthquake appropriate access to fire station is important.	Habibi et al, 2007	Tehran Municipality

3.2 AHP model construction

The problem should be stated clearly and decomposed into a rational parts, like a hierarchical model. The AHP model in this paper consists of three levels. The first level is decision problem of accessing the earthquake vulnerability. The second level is the criteria or the determinants upon which the assessment of vulnerability is broadly based. This level is divided into three major components: Land base, Constructional base and Access base criteria. The next level consists of the sub criteria that support the determinants (Figure 2).

Figure 2. AHP model

3.3 Pair wise comparison and local weights

A pair wise comparison is a numerical representation of the relationship between two elements that discerns which element is more important, according to a higher criterion. Saaty (1980, 1994) proposed a scale of 1–9, where 1 represents equal importance; that is, the two elements contribute equally to the objective, while 9 represents extreme importance that is favours one element (row component) over another (column component). If the element has a weaker impact than its comparison element, the score range varies from 1, indicating indifference, to 1/9, an over whelming dominance by a column element over the row element. For reverse comparison of the elements, the corresponding reciprocal value is assigned, so that the matrix “ $a_{ij} \cdot a_{ji} = 1$ ”.

Table 2. Saaty’s 1-9 scale for AHP preference

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one over another
5	Strong importance	Experience and judgment strongly favour one over another
7	Very strong importance	Activity is strongly favoured and its dominance is demonstrated in practice
9	Absolute importance	Importance of one over another affirmed on the highest possible order
2, 4, 6, 8	Intermediate values	Used to represent compromise between the priorities listed above
Reciprocal of above non-zero numbers	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	

(Saaty, 1996)

In the presented model there are about 4 pair wise matrices. In order to perform the pair wise comparisons, about 8 face to face interviews were held with the experts in earthquake and urban planning by making use a comprehensive questionnaire. As a result of these interviews and judgments, weights of the main criteria and subcriteria were determined using Expert choice

software (Version 9.48s25). After carrying out all the comparisons and determining the weights, consistency ratio of all the pair wise comparisons matrices and those of the judgments were calculated. The consistency measure is very useful for identifying possible errors in judgments. If the inconsistency ratios of all the pair wise comparisons matrices are less than 0.1, all comparisons matrices are consistent and judgments are reliable. In this study, the inconsistency ratios (CR) of all the comparisons matrices were less than 0.1 and so all of the judgments were accepted as reliable.

Table 3. Pair wise comparison of main criteria and their weights

Criteria	Land Base	Constructional Base	Access Base	Weights
Land Base	1	0.48	2.9	0.290
Constructional Base	2.1	1	6.2	0.610
Access Base	0.35	0.16	1	0.100

CR=0

Table 4. Weights of the sub criteria

Criteria	Subcriteria	Weights		
Land Base	Land use	0.375	-	-
	Area	0.223	-	-
	Geometrical Shape	0.082	-	-
	Parcel location in the block	0.189	-	-
	Population density	0.131	-	-
Constructional Base	Type of the structure	-	0.512	-
	Age of building	-	0.110	-
	Quality of construction	-	0.085	-
	Number of stories	-	0.1	-
	Occupy Ratio	-	0.065	-
	Constructional density	-	0.128	-
	Road width	-	-	0.560
Access Base	Access to Open Space	-	-	0.158
	Access to Rescue Center	-	-	0.197
	Access to Fire Station	-	-	0.085

3.4 Final weights of criterions

Weights of subcriteria are local weights and they must be finalized to apply in assessment. For this, local weights of each subcriteria must be multiplied to weight of related upper level criteria (Eq .1).

$$fw_{ij} = w_i * w_{ij}, \sum fw_{ij} = 1, i, j = 1, \dots, n$$

Equation 1. Final weight

Where fw_{ij} = final weight of C_{ij} (subcriteria), w_i = weight of C_i (main criteria).

Final weight of each evaluation factor was determined represented in the Table 5.

Table 5. Final importance ratios of each criterion

Criteria	Value
Land Use	0.10875
Area	0.06467
Geometrical Shape	0.02378
Parcel location in the block	0.05481
Population density	0.03799
Type of the structure	0.31232
Age of building	0.0671
Quality of construction	0.05185
Number of stories	0.061
Occupy Ratio	0.03965
Density	0.07808
Road width	0.056
Open space	0.0158
Rescue center	0.0197
Fire Station	0.0085

3.5 The Criteria Normalization

The criteria used in the present paper for the earthquake vulnerability assessment should be normalized. For this purpose the criteria have converted from classic state to the fuzzy and unscaled condition using the fuzzy logic and the linear threshold function. The fuzzy logic function is proposed by a professor LotfiZadeh. This function provides a space for reasoning, control and decision making in uncertainty situation ([Habibi, et al. 2007](#))

$$f_w = \{ 0 \text{ if } x < a, (x - x_{\min}) / \Delta x \text{ if } a < x < b, 1 \text{ if } b < x \}$$

Equation 2. Fuzzy logic function

([Habibi, et al. 2007](#))

In this equation, $f(x)$ is fuzzy function, x is the criterion, a and b are the minimum and maximum acceptable value for the specific criteria and Δx is the difference between a and b . By using the proposal of experts in earthquake and according to the mentioned function, the fuzzy functions for all the criteria have been achieved. Due to brevity, in this section the graphs which show the functions for each criterion are shown in Table 6.

Table 6. Fuzzy functions for the criteria

4. DATA ANALYSIS IN THE CASE STUDY

The studied area is located in the central part of the 6th district of Tehran municipality. This area is determinate by Shohadae Gomnan highway in the north and west, the Fatemi Boulevard in the west and the Kargar Boulevard in the south. Its area is 95 hectares and has about 2080 inhabitants ([Iran statistical Center, 2006](#)).

Figure 2. Location of the study area

This section surveys the mentioned criteria for earthquake vulnerability assessment in the study area (see Table 1). According to the obtained fuzzy functions in previous section, for each parcel a numerical fuzzy value is acquired. The results of surveys and fuzzy values can be illustrated in the mode of map, chart and graph. So 15 different data layers are produced which show the existent condition of a specific criterion in the studied area. To be concise, in

this section 6 of these 15 maps are shown (Figure 4 to Figure 9).

Figure 3. Land use in the studied area

Figure 4. Plot areas in the studied area

Figure 5. Type of Structure in the studied area

Figure 6. Constructional Density in the studied area

It should be noted that for criteria such as access to open spaces, rescue centers and fire stations, the Network Analyst tool in the GIS environment has been used. Its advantage in comparison to similar tools such as Buffer is measuring the real distance in relation to the existent roads, not the direct distance on the map.

Figure 7. Access to Open Spaces in the studied area

Figure 8. Access to Rescue Centers in the studied area

5. VULNERABILITY ASSESSMENT

The probability function has been used for the earthquake vulnerability assessment. The consequent vulnerability function due to the criteria has been defined. In this function the w_i is the importance ratio for a specific criterion, which was calculated by the AHP model (see Table 5) and $f(x)$ is the fuzzy numerical value obtained for the each parcel from the criterion (see Table 6).

$$p(w) = \sum_{i=1}^n w_i * f(x)$$

Equation 3. Fuzzy numerical value function (vulnerability function) ([Habibi, et al. 2007](#))

The vulnerability function represents a numerical value between 0 and 100 percent for each parcel which shows the consequent vulnerability of each parcel due to the criteria. The parcels with more vulnerability have greater scores. The vulnerability numbers in the studied area are between 0.1 and 0.7. As a parcel doesn't obtain the minimum and maximum numerical fuzzy value for all the criteria, the consequent vulnerability doesn't reach the 0 and 100 percent (Table 7 and Figure 10).

Table 7. The vulnerability numbers for each parcel

Category of vulnerability	Parcels number	Parcels percentage	Parcels percentage
0 – 0.1	2	0.07	1.47
0.1 – 0.2	36	1.4	
0.2 – 0.3	30	1.16	10.7
0.3 – 0.4	246	9.54	
0.4 – 0.5	1606	62.3	
0.5 – 0.6	631	24.48	87.83
0.6 – 0.7	27	1.05	
Sum	2578	100	100

Figure 9. The consequent vulnerability in the studied area

6. CONCLUSIONS

In a real scenario, urban managers, planners and other experts in earthquake vulnerability assessment and mitigation require software tools that produce efficacious results, are easy to use and comprehend, and which require a moderate duration to arrive upon results. Therefore, in this paper an attempt has been made:

- I. To develop a comprehensive methodology incorporates divers criteria involved in assessing the earthquake vulnerability.
- II. To solve the problem of assessing the earthquake vulnerability in an urban area; in the paper, this problem is solved through the Analytic Hierarchy Process. AHP enables to break the problem up in a systematic and logical way which helps to handle the complexity of the problem.
- III. To normalize the criteria and converting theme to an unscaled condition, by using the fuzzy logic and linear threshold function which allocated each parcel a specific numerical value for a criterion.
- IV. To establish the vulnerability function and allocating each parcel a specific number which represents the consequent vulnerability due to criteria.

The produced earthquake vulnerability map provides sustainable information for developing the earthquake mitigation programs, the land planning design of future infrastructure, the planning of crises confrontation procedures, etc. Based on the information provided from the earthquake vulnerability map locations with more vulnerability are recognized. This map can provide information concerning the selection of proper location for construction of vital infrastructure during a crises situation. (e.g. a hospital, fire stations, etc).

The above mentioned examples and numerous other application of the vulnerability map's information appoint their importance for the protection of the cities and build environments against earthquakes and justify the obligation of states, municipalities and others, who are responsible for making safe places in the neighbourhoods to provide theme for every city.

There were some limitations in this research that affected on research results. Inaccuracy and being out of date maps were two limitations that caused the vulnerability map be not accurate. These limitations can be removed by providing up to date to achieve useful results. About the criteria that used in assessment procedure, it can be said that there are other criteria that can be used in this model. For example, geological criteria such as adjacency to faults, can be fitted to this model appropriately. By gathering these information, the result of assessment can be more accurate and useful. But the important output of this assessment, is using its result for reducing earthquake damages and deaths. The weights of criteria show that some criteria such as Land use, Type of structure and Density have more weights. By improving these criteria and control of constructional by regulation, the building damages can be reduced. For example, about the land use criterion, the municipality can provide regulation for control construction more effectively. So, providing vulnerability map is first step for reducing earthquake damages and deaths. The urban managers and urban policy making are responsible for the next steps.

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