

Modeling of Urban Building Vulnerability in Earthquake against Using Analytical Hierarchy Process (AHP) and GIS

A case study on Zanjan City, Northwest of Iran

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Abstract

Rapid assessment of the damaged buildings in a disastrous event is a drastic measure to be taken in order to allocate shelter to unsheltered people as quick as possible. Natural disaster as earthquake may cause considerable losses to the cities and prevent development processes. Urban planning as well as city designing projects aims to decrease vulnerability of buildings against earthquake. In this direction, the first step is to recognize and analyze the rate of damages exerted to every urban element using proper models.

Spatial data along with attributes of building elements and their behaviors against earthquake shocks has been employed using Analytical Hierarchy Process (AHP) to evaluate the vulnerability of the city against earthquake shocks. Also the weight of every criterion in building destruction has been determined through this method using GIS analysis. Damages and life losses in different districts of the city were assessed and an earthquake zoning map of the city prepared for different earthquake intensities.

The results disclosed that region 3 of Zanjan are due to very high degree of damage because of the old building as well as using low quality building material while region 2 of the city is the least vulnerable area due to using the stronger building material and applying the construction standard as the 2800 construction act.

Keywords: vulnerability, Earthquake, Zanjan, GIS, Modeling, AHP

Introduction:

During the 20th century, more than 1,100 strong earthquakes have occurred, causing more than 1,500,000 casualties. Most of them are due to buildings collapsing, which is some 90% of direct deaths. Advances in structural design were applied to new structures

and, to a lesser extent, to the rehabilitation of existing structures. Nevertheless, there are many more old structures than newly constructed ones. Main and likely the only way to lessen risks in urban areas is to reduce building vulnerability (Lantada, 2008, 2).

It is obvious that the major cause to increase life losses is building collapse that is due to negligence of those who were in charge of construction projects as well as urban planning. It is experienced that those countries proven to earthquake hazards may reduce the rate of losses by strengthening their buildings (Mahdian, 2002, 9). The best example is Japan which experiences several strong earthquake year leaving very few losses. Proper urban infrastructure is the major reason for less damage preventing crisis in this country. Earthquakes in Iran and neighboring regions (e.g., Turkey and Afghanistan) are closely related to their position within the geologically active Alpine-Himalayan Belt.

Many Iranian cities are susceptible to earthquake hazard due to their geologic setting. Historic records show many Iranian cities have been suffering by earthquake shocks leaving many lives and economic losses.

Zanjan province is one of these earthquakes proven areas that suffered one of the most destructive earthquakes of 7.2 in Richter scale in 1990. The quake occurred in Rodbar- Manjile area in north of Zanjan leaving over 40,000 death and destructing 300 villages. Another destructive earthquake occurred in Khodabande area in 2000 leaving 500 deaths (Abdi, 2006, 2).

However, the city of Zanjan has not yet experienced a major destructive earthquake such as Bam, Boein-Zahra, Tabas and others but we cannot take this as a positive sign. If the 5.4 Richter scale earthquake which shocked southwest of Zanjan in 2008 would last a bit longer or stronger quake would occurred we were faced another tragic event .

The fourth development plan of the country aims to reduce the vulnerability of the Iranian cities against natural disasters including earthquake. For this purpose, a comprehensive study should be conducted to assess the vulnerability of major cities, towns and villages so proper urban planning projects should be executed. Besides that necessary measures should be taken to strengthen the buildings against earthquake in order to reduce the rate of losses.

Background

Vulnerability assessment and earthquake modeling of Iranian cities against earthquake using Analytical Hierarchy Process (AHP) have not yet been employed. The only experience in this concern relates to sampling from the buildings in order to apply for the whole city. The reasons for insufficient study are as following:

The lack of spatial and non-spatial data, the lack of GIS based database, and the lack of city risk zoning map .All these deficiencies make decision-making process very difficult before and after a natural disaster.

All researches in this regards were based on the building census and the building census were made only as blocks instead of single building, therefore the results are not reliable. Main researches in this regard are made by the followings:

AgaTaher and et al (2006), weighting the effective factors in vulnerability of Tehran against earthquake. Ahadnejad and et al (2007), assessment of the urban fringe of Zanzan against earthquake using GIS. Azizi and Akbari (2008), urban development remarks in measuring urban vulnerability against earthquake in a GIS system using Analytical Hierarchy Process (AHP). Silavi and etal(1384), preparing the earthquake risk map using multi criteria decision-making method based on mathematics and spatial information systems.

Many researchers have been conducted In relation to earthquake modeling and vulnerability assessment of the city using in other countries using Analytical Hierarchy Process (AHP). Major studies are as followings:

Rashed and et al(2003), earthquake hazard modeling and hazard forecasting of cities using remote sensing and GIS and the role of GIS in forecasting the vulnerability of a city against earthquake. Sejian et al (2004), evaluating the risk of firing after an earthquake using GIS. Mahmet(2004), earthquake vulnerability assessment using multi criterion spatial data analysis. Kepeng(2001), decision making for natural disaster events using the combination of GIS and multi criterion evaluation method.

The present study endeavored to eliminate the insufficiencies of the previous studies and vulnerability modeling is created based on every single building using field measurements and high-resolution satellite imageries.

In addition, Analytical Hierarchy Process (AHP) based on main and subordinate building elements have been employed in order to model the earthquake hazard in Zanzan in GIS. Damages and life loses in different districts of the city were assessed and an earthquake zoning map of the city prepared for different earthquake intensities.

Method and materials:

In this research, efforts have been made to discover the relation between the cause and effect. Through qualitative and quantitative methods as well as the analysis of the relations governing them are used to prove the proposed hypothesis. Needed data including building

properties and urban architecture extracted from 1:2000 scale maps of the city and satellite imageries.

The employed data for the research is classified into spatial and non spatial data including: construction material, the age of building, the number of floors, building use, the area, the area of blocks; the position of building in the block, the number of neighboring blocks, Façade materials.

Different methods have already been used to evaluate the vulnerability of cities against earthquake. One of the used methods is multi-criterion analysis. This method combines spatial data and attributes as an input and finally calculates the degree of vulnerability of every building element against the earthquake (output), also combining this method with fuzzy logic in GIS, vulnerability of the cities against the earthquake may be assessed with higher accuracy(Rashed, 2003,6).

Vulnerability of the city of Zanzan against earthquake stressed using Analytical Hierarchy Process and multi-criterion analysis in this study. As indicated in table 1 ten parameters were selected In order to do vulnerability assessment (figure 1).

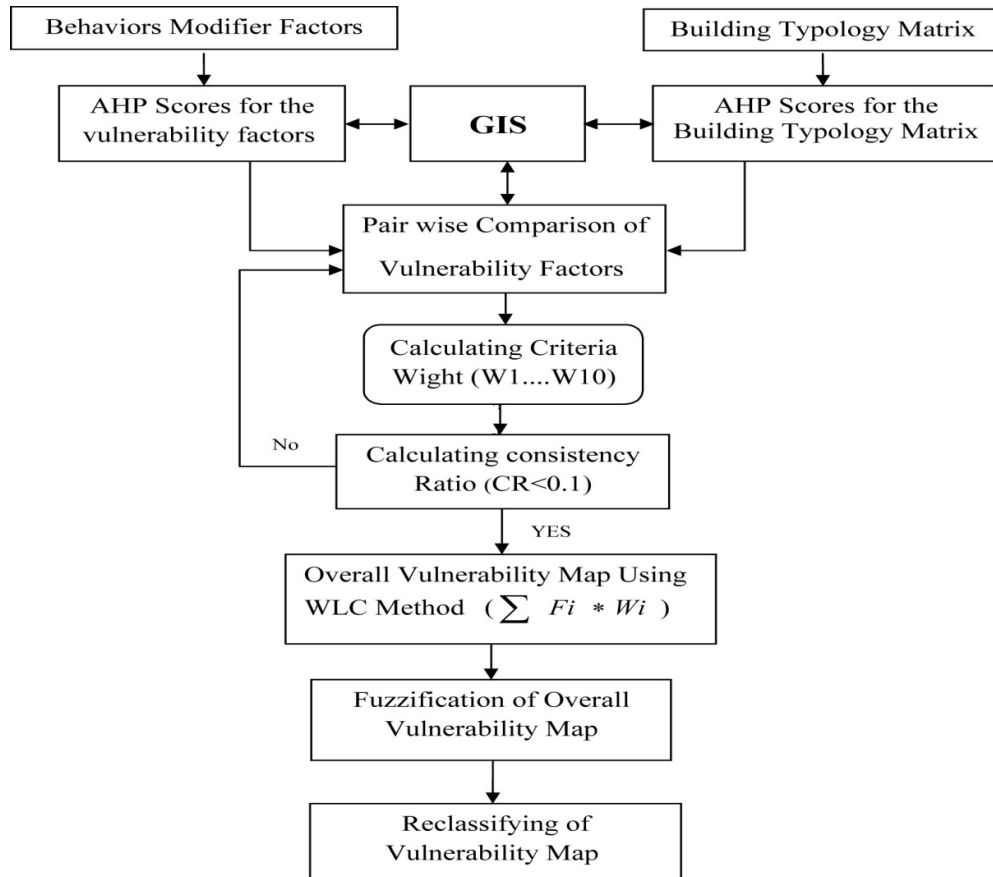


Fig 1: flow chart of the research

Table1: factors affecting vulnerability of the building along with their weights

Main Criteria	Following Criteria	Very High Vulnerability	High Vulnerability	Medium Vulnerability	Low Vulnerability	Very Low Vulnerability
Material Type	Wight	9	7	5	3	2
	Steel					•
	Concrete				•	
	Brick and Steel			•		
	Brick and wood		•			
	Bricks-Adobe -Wood		•			
	Adobe and wood	•				
Age of Building	Before 1950	•				
	1950-1970		•			
	1970-1980			•		
	1980-1990				•	
	1990-2000					•
	2000-2008					•
Quality of Building	New					•
	Restoration			•		
	Destructive	•				
	Ruin	•				
Number of Floors	1 floors					•
	2 floors				•	
	3 floors			•		
	4 floors		•			
	5 and more floors	•				
Rate of occupation	0-25%				•	
	25-50%			•		
	50-75%		•			
	75-100%	•				
Land use	Residential		•			
	Commercials			•		
	Educational				•	
	Equipment					•
	Official and Military					•
Area of Parcel	Less Than 100m2	•				
	100-250 m2		•			
	250-500m2			•		
	More than 500m2				•	
Position of building in the block	Middle				•	
	Side			•		
	Individual		•			
Number of Neighborhood	Without	•				
	1 Neighborhood		•			
	2 Neighborhood			•		
	3 and More				•	
Facade materials	Glass		•			
	Thatch			•		
	Brick				•	
	Cement and Stone					•

The Concept of AHP model:

Analytical Hierarchy Process (AHP) is a very simple, flexible and effective method to ease decision making process when different contradictory criteria make decision making process difficult. This method proposed by Thomas L Sati in 1980 and has been used for several times in different sciences. (Zebardast, 2001,1). This method considerably reduces the complexity of decision making process since only two components are simultaneously being studied (binary comparison). The method includes three major steps as: A) generating of two comparison matrices B) weight calculation for different factors. C) Agreement ratio calculation. The mentioned steps have been applied to model the vulnerability of the city against earthquake.

A: *Generating of a binary comparison matrices*

This method employed a 1-9 scale to determine the priority of two criteria (table 1). In fact in order to determine the weight of every factor they are compared together. The results are recorded in metric $n \times n$ (in this case 10×10) which is called as binary comparison metric $A_{ij}=[a^{n \times n}]$. All components of the mentioned metric are positive and regarding the "reverse condition" in Analytical Hierarchy Process (if the weight of i in relation to j equals to k , the weight of j in relation to i will equal to $1/k$) we will have two numerical quantity of A_{ij} and $1/a_{ij}$ in every binary comparison.(Zebardast (2001,3) has proposed the binary comparison metric in table 2.

Table 2: The nine level scale for binary comparison of different options

<i>Description</i>	<i>Weight</i>
1	equal weight
2	equal – moderate
3	moderate
4	Moderate – strong
5	Strong
6	Strong-very strong
7	Very strong
8	Very strong-extremely strong
9	Extremely strong

Previous studies and reports as well as remarks made by experts in this concern have been used to determine effective structural factors in building vulnerability against earthquake. The results have been summarized in table 3. Every affecting criteria has been applied in GIS as a layer to be used in analyzing the overall vulnerability.

B) Weight calculation for different factors:

This step includes the followings:

- 1- Multiplying the amount of every row in the binary comparison metric by each other which are illustrated in the following equation. (Thapalia, 2006,52)

$$RMV = \sum \text{factor1} * \text{factor2} * \dots * \text{factorN} = 9 * 9 * 9 * \dots * 9 = 387420849$$

- 2- Calculating of all unnormalized weights .In order to obtain this factor the sum of products for every row were applied to the power of 1/n which are the number of influencing factors.

$$[(RMV)^{1/\text{Factor}}] = (387420849)^{1/10} = 7.225$$

- 3- finally to calculate the weight of criteria,

$$\text{Wights} = [(RMV)^{1/\text{Factor}}]_{\text{firstRow}} / \text{Sum}[(RMV)^{1/\text{Factor}}] = 7.225/15.860 = 0.458$$

Unnormalized weights in every row are divided by the sum of unnormalized weights.

The above equation revealed that the highest weight belongs to building material used in framework of the buildings and the rest of factors depend on the other used building material. So building strength against earthquake mainly depends on the strength of used material, applying the related engineering standards and regulations as well. The weight of other criteria used in this research respectively attain medium to weak and they have been sorted in respect of their significance in building vulnerability.

Table3: Pairwise comparison of ten vulnerability factors

Criteria	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	Row Multiplied Value(RMV)	Un normalized Value	Normalized Value
Material Type(1)	1	9	9	9	9	9	9	9	9	9	387420849	7.225	0.458
Age of Building(2)	0.11	1	2	2	3	3	4	4	5	7	2237.76	2.163	0.136
Quality of Building(3)	0.11	0.5	1	2	2	3	3	3	3	5	89.91	1.568	0.099
Number of Floors(4)	0.11	0.5	0.50	1	2	2	2	3	3	4	7.992	1.231	0.075
Rate of occupation(5)	0.11	0.33	0.50	0.50	1	2	2	3	3	3	0.998	1	0.062
Land Use(6)	0.11	0.33	0.33	0.50	0.50	1	2	2	3	3	0.111	0.803	0.053
Area of Parcel(7)	0.11	0.25	0.33	0.50	0.50	0.5	1	2	2	3	0.014	0.652	0.040
position of building in the block(8)	0.11	0.25	0.33	0.33	0.33	0.5	0.5	1	2	2	0.001	0.502	0.030
Number of Neighborhood(9)	0.11	0.20	0.33	0.33	0.33	0.3	0.5	0.5	1	2	0.00001	0.411	0.026
Facade materials(10)	0.11	0.14	0.20	0.23	0.33	0.3	0.3	0.5	0.5	1	0.000007	0.307	0.019
Total											387422826	15.860	1

C: The adaptive ratio estimation

AHP method avails to investigate the compatibility of judgments to determine the significance of criteria and sub criteria. In other word AHP method helps us to understand how much compatibility were achieved in creating the binary comparison metric (table 4)? There is a high degree of discordance in judgments if the weight of different criteria evaluated in compare to each other. Meaning that if A_i weights higher than A_j and A_j has higher weight than A_k , A_i should attain higher weight than A_k . But in spite of all efforts the people's priorities are usually discordant. Therefore we need to find a procedure to disclose the degree of discordance in judgments.(Zebardast, 2001, 42). In order to determine the adaptive ratio, the following steps should be taken:

- 1- Calculation of AW vector: AW vector is calculated through multiplying the binary comparison matrices by the calculated weight for every criteria (table 4).
- 2- Calculation of adaptive vector: in order to calculate the adaptive vector in AHP method the following equation is used in which the calculated numerical value for every vector is divided by every criteria and then multiplied by 1/n (equation 4).

Table 4: binary comparison matrices of the evaluated criteria to estimate adaptive ratio

$$\begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \end{matrix} \begin{bmatrix} 1 & 9 & 9 & 9 & 9 & 9 & 9 & 9 & 9 & 9 \\ 0.11 & 1 & 2 & 2 & 3 & 3 & 4 & 4 & 5 & 7 \\ 0.11 & 0.50 & 1 & 2 & 2 & 3 & 3 & 3 & 3 & 5 \\ 0.11 & 0.50 & 0.50 & 1 & 2 & 2 & 2 & 3 & 3 & 4 \\ 0.11 & 0.33 & 0.50 & 0.50 & 1 & 2 & 2 & 3 & 3 & 3 \\ 0.11 & 0.33 & 0.33 & 0.50 & 0.50 & 1 & 2 & 2 & 3 & 3 \\ 0.11 & 0.25 & 0.33 & 0.50 & 0.50 & 0.50 & 1 & 2 & 2 & 3 \\ 0.11 & 0.25 & 0.33 & 0.33 & 0.33 & 0.50 & 0.50 & 1 & 2 & 2 \\ 0.11 & 0.20 & 0.33 & 0.33 & 0.33 & 0.33 & 0.50 & 0.50 & 1 & 2 \\ 0.11 & 0.14 & 0.20 & 0.25 & 0.33 & 0.33 & 0.33 & 0.50 & 0.50 & 1 \end{bmatrix} \times \begin{bmatrix} 0.458 \\ 0.138 \\ 0.099 \\ 0.075 \\ 0.062 \\ 0.053 \\ 0.040 \\ 0.030 \\ 0.026 \\ 0.019 \end{bmatrix} = \begin{bmatrix} 5.335 \\ 1.429 \\ 1.038 \\ 0.801 \\ 0.659 \\ 0.528 \\ 0.424 \\ 0.331 \\ 0.274 \\ 0.208 \end{bmatrix}$$

$$L = \frac{1}{n} \left[\sum_{i=1}^n (Aw/Wi) \right]$$

$$L = \frac{1}{10} \left[\frac{5.335}{0.458} + \frac{1.429}{0.138} + \frac{1.038}{0.099} + \frac{0.801}{0.075} + \frac{0.659}{0.062} + \frac{0.528}{0.053} + \frac{0.424}{0.040} + \frac{0.331}{0.030} + \frac{0.274}{0.026} + \frac{0.208}{0.019} \right] = 10.659$$

- 3- Calculation of adaptive index: when adaptive vector is calculated, compatibility index should be calculated for all criteria. To calculate such index the following equation is employed:

$$CI = \frac{L - n}{n - 1} = \frac{10.659 - 10}{10 - 1} = 0.073$$

4- Adaptive ratio is calculated using the following equation:

$$CR = \frac{CI}{RI} = \frac{0.073}{1.49} = 0.0491$$

RI indicates the random index in the above equation which is derived from the following table:

Table no 5: the random index

15	14	13	12	11	10	9	8	7	6	5	4	3	2	n
1.59	1.57	1.56	1.48	1.51	1.49	1.45	1.41	1.32	1.24	1.12	0.9	0.58	0	RI

If CR (adaptive ratio) is equal or smaller than 0.1, it means that there is concordance in judgments and if Cr is greater than 0.1, the judgments should be reconsidered. In present study the CR is estimated as 0.0493 meaning that there is a concordance in judgments.

Evaluation of the overall vulnerability:

In order to evaluate the overall vulnerability, the weights for every criteria is calculated using AHP method and then every weight has been applied for its related layer using GIS software and then vulnerability map of Zanjan against earthquake is prepared.

Fuzzy maps of the overall vulnerability:

Since the evaluation criteria in offered by different scales , therefore in order to convert them for a uniform scale it is needed to be standardized .Besides the fuzzy theory there are several other methods for standardization such as linear scale transform function ; value function; and the probability of reconsideration. Since the Fuzzy logic encompasses a wide range of functions in compare to the other standardization methods therefore it is considered as a effective method in using the approximate data and information for decision making (Rashed , 2003, 7).

Considering the above mentioned reason the fuzzy method has been employed to standardize the overall vulnerability (figure2).

The results disclosed that region 3 of Zanjan are due to very high degree of damage because of the old building as well as using low quality building material while region 2 of the city is the least vulnerable area due to using the stronger

building material and applying the construction standard as the 2800 construction act.(Table 6)



Fig 2: overall vulnerability based on the used criteria using AHP

Table 6: The vulnerability zonation of Zanjan city based on municipality region

Vulnerability Range	Region1		Region2		Region3	
	Number of Building	Area (Hectare)	Number of Building	Area (Hectare)	Number of Building	Area (Hectare)
Very low vulnerability (0-0.2)	4928	119.75	12069	367.92	658	20.42
low vulnerability (0.2-0.4)	2447	39.93	2430	71.43	663	19.21
Medium vulnerability (0.4-0.6)	14524	206.52	10936	249.78	7949	139.56
High vulnerability (0.6-0.8)	2937	38.35	1951	26.41	2221	39.36
Very High vulnerability (0.8-1)	219	3.97	188	2.90	548	11.17
Total	25055	408.52	27574	718.44	12039	229.72

Conclusions:

The vulnerability of a city is called to losses imposed to urban components in case of a disaster and its intensity may vary based on its nature and quality. Vulnerability of a city is an extensive factor encompasses all existing in a city and since all components in a city are connected to each other therefore it increases very quickly (Poian 1999, 2).

Due to lack of digital spatial data throughout the country risk zoning map against earthquake have not been prepared for Iranian cities. Other studies in this concern are mostly based on statistics and housing census which is done as pilot and in some cases applied for the whole country therefore an accurate analysis of the vulnerable urban elements against earthquake has not been yet achieved.

All involving factors in vulnerability study may not be considered as a whole therefore AHP method has been employed at present study for weighting the major building components as well as their behavior which obey the fuzzy logic. Also the results are compiled using GIS to simulate earthquakes with different intensities. Consequently the vulnerability of the city modeled and risk zoning map were prepared considering building and economic losses for different earthquake intensities.

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