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Discussions

GIS modelling of seismic vulnerability of residential fabrics considering geotechnical, structural, social and physical distance indicators in Tehran city using multi-criteria decision-making (MCDM) techniques

F. Rezaie and M. Panahi

Department of Geophysics, Young Researchers and Elites Club, North Tehran Branch, Islamic Azad University, Tehran, Iran

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Correspondence to: F. Rezaie (rezaiee.1984@gmail.com)

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Abstract

The main issue in determining the seismic vulnerability is having a comprehensive view to all probable damages related to earthquake occurrence. Therefore, taking factors such as peak ground acceleration (PGA) in the time of earthquake occurrence, the type of structures, population distribution among different age groups, level of education, the physical distance to a hospitals (or medical care centers), etc. into account and categorized under four indicators of geotechnical, structural, social and physical distance to needed facilities and distance from dangerous ones will provide us with a better and more exact outcome. To this end in this paper using analytic hierarchy process (AHP), the amount of importance of criteria or alternatives are determined and using geographical information system (GIS), the vulnerability of Tehran metropolitan as a result of an earthquake, is studied. This study focuses on the fact that Tehran is surrounded by three active and major faults of the Mosha, North Tehran and Rey. In order to comprehensively determine the vulnerability, three scenarios are developed. In each scenario, seismic vulnerability of different areas in Tehran city is analysed and classified into four levels including high, medium, low and safe. The results show that regarding seismic vulnerability, the faults of Mosha, North Tehran and Rey respectively make 6, 16 and 10 % of Tehran area highly vulnerable and also 34, 14 and 27 % are safe.

1 Introduction

The Iranian plateau is located between two plates of Eurasia and Arabia as a part of Alp-Himalaya orogenic belt and is among the world's most active seismic areas. Tectonic activities in this scope are the result of northward Arabian plate movement towards Eurasia and reveal the convergence of these two plates (Berberian, 1981; Hessami et al., 2001; Allen et al., 2004). GPS studies show that Arabian plate is moving about from 21 to 25 mm northward each year (Sella et al., 2002; Vernant et al., 2004).

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The result of this movement on the Iranian plateau is varied due to the existence of different geological structures in different locations (Hessami et al., 2006) such that the amount of movement in east of Iran in Makran subduction zone is up to 18 mm per year and 8 mm in Kopeh Dagh. There are also westward movements of about 8 mm per year on Zagros and Alborz Mountains (Fu et al., 2007). These overall movements have created heavy physical and financial damages to the area. An example is the Bam earthquake (2003, $M_w = 6.6$) which left over 30 000 killed, 10 000 injured, 100 000 homeless and devastated more than 80 % of the houses (National Report of the Islamic Republic of Iran on Disaster Reduction, 2005). Statistically, it can also be stated that during the last 100 years, the Iranian plateau has experienced 14 major earthquakes with the magnitude of 7 (on Richter scale) and also 51 earthquakes with the magnitude of 6 to 7. Earthquakes in Buyin-Zahra (1962, $M_s = 7.3$), Dasht Bayaz (1968, $M_s = 7.3$), Tabas (1978, $M_s = 7.8$), Sirch (1981, $M_s = 7.3$), Manjil (1990, $M_s = 7.7$) are examples of it (Mahdi and Mahdi, 2013).

Tehran metropolitan (as Iran's capital) has a population of around 12 million people. As a result of the city being located in the vicinity of three active faults of the Mosha, North Tehran and Rey, it has high seismic vulnerability potential. The study of earthquakes' catalogue proves this claim. Therefore, developing a vulnerability map against earthquake for Tehran is of utmost importance.

Since several factors determine the seismic vulnerability of a city and all of them have to be studied simultaneously, in order to fill this gap, multi-criteria decision-making (MCDM) techniques can be used. MCDM follows a collection of methods, through which techniques and algorithms utilized to solve complex decision-making covering a wide range of choices and assessed by multiple, conflicting and incommensurable criteria as well as developing, assessing and prioritizing of decision-making alternatives can be used (Malczewski, 1999; Suárez-Vega et al., 2011). Since GIS facilitates the vulnerability studies and natural hazards analysis as a useful tool for managing, controlling, processing and analyzing the spatial data (Rashed and Weeks, 2003; Gamper et al., 2006; Almasri, 2008), utilizing GIS-based multi-criteria decision-making

(GIS-MCDM) developed by Malczewski (2006) provides the possibility of prioritizing and combining the spatial criteria from different location and description viewpoints and eventually making comprehensive decisions. Different GIS-MCDM techniques are available depending on the required operations in order to acquire the final assessment from alternative solutions; and AHP is one of them.

AHP is one of the most comprehensive algorithms developed for decision-making with multi-criteria; since this method allows for hierarchically formulizing the complex problems and there is also the possibility of considering different quality and quantity criteria simultaneously (Chen et al., 2008). Thus, in solving complex spatial problems, the combination of AHP with GIS resolves many issues. As a result, a great body of research has been conducted to assess the vulnerability of cities against natural events including earthquake via AHP and GIS, among which Chen et al. (2001), Rashed and Weeks (2003), Cutter et al. (2003), Servi (2004), Ebert et al. (2009), Schmidtlein et al. (2008), Botero Fernández (2009), Nefeslioglu et al. (2013) are only examples.

This study takes into account three seismic scenarios for the faults of the Mosha, North Tehran and Rey in order to assess the seismic vulnerability of Tehran. To this end, not only geotechnical index, but also with reviewing the literature and expert opinion and the experience of past earthquakes in Iran, other influential factors in seismic vulnerability of cities including the type of structures, population distribution in different age groups, level of education and distance to road network that are categorized in three indicators including structural, social, and physical distance to needed facilities and distance from dangerous ones are taken into account. Each of these criteria (indicators) is divided into alternatives (sub-indicators) in itself. In next step, to get the weight of each criteria or alternatives, AHP and pairwise comparison of criteria and alternatives are used. Then using GIS, the criteria or alternatives are combined regarding the gained weight. Eventually, three seismic vulnerability maps are developed for Tehran city based on three possible earthquakes resulting from the activity of each aforementioned fault.

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2 The study area

Tehran metropolitan lies at the latitudes 51°15′ and 51°35′E and the longitudes 35°33′ and 35°50′N . The city has experienced a major wave of migration due to economical, welfare and cultural issues during the last three decades. The metropolitan's population has increased from around 11 million in 2006 to 12 million in 2011 (average growth of 1.44 per year) (Seifolddini and Mansourian, 2014). Therefore the scope is one of the metropolitans in Iran as well as in the world. Tehran municipality officials have taken many factors into consideration in addition to the population and divided the city into 22 districts to provide better services to the citizens. On the other hand, Tehran is located on the southern foothills of Alborz Mountains in the vicinity of three active faults of the Mosha, North Tehran and Rey which makes the city seismically a matter of concern. The analysis of the earthquakes up to 100 km away (Fig. 1) shows the seismic status of the scope.

As the catalogues of earthquakes and seismotectonic studies show, a part of earthquake occurrences in Tehran is the result of movement on the three following active faults:

1. The Mosha fault was first described as a reverse fault dipping north by Berberian et al. (1985) and Tchalenko et al. (1974) is ~ 175 km long at the southern edge of the Alborz Mountains. The Mosha fault is composed of 3 segments with a slightly different orientation (Landgraf et al., 2009). The strike of this fault changes in the western segment from ~ EW to WNW–ESE in the central segment. The eastern segment strikes WNW–ESE (Tatar et al., 2012) and has left-lateral motion along a north-dipping plane (Allen et al., 2004; Bachmanov et al., 2004) but with a slight normal component (Ritz et al., 2006). The Mosha has been the cause of big historical earthquakes with magnitudes of over 6.5 in AD 958 ($M_s \sim 7.7$), AD 1665 ($M_s \sim 6.5$), AD 1830 ($M_s \sim 7.1$) (Berberian and Yeats, 2001).

2. The North Tehran fault is composed of faults which lie in north and west of Tehran with the estimated length of 110 km (Tchalenko et al., 1974; Berberian et al.,

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1985). The strike of eastern part of the fault is ENE-WSW which dips northward and the western part of it is NW–SE. The dip of this fault is between 10° to 80°. The focal mechanism of the North Tehran fault is thrust with a component of left lateral strike slip motion (Nazari, 2006). Since the North Tehran fault is a seismically active fault, it is probable that the historical earthquakes with the magnitude of $M_s \sim 7.1$ and $M_s \sim 7.3$ respectively 855–856 (exact year is uncertain) and 1177 have occurred due to rupture of this fault (Ashtari Jafari, 2010).

3. The faults of North and South Rey named originally by Berberian et al. (1985) are respectively 20 and 16.5 km. They are 3 to 5 km away from each other. Since the eastern and western strikes of these faults are buried under the young fluvial sediments, their dip is unrecognizable from the ground but the geometric shape of it on the ground shows north-dipping thrust faults. According to the studies conducted by Berberian and Yeats (1999 and 2001) the occurrence of the historical earthquakes of 855 ($M_s \sim 7.1$), 864 ($M_s \sim 5.3$), 958 ($M_s \sim 7.7$), 1177 ($M_s \sim 7.2$) could be the result of these faults' movements.

Therefore, due to the high seismic activity rate and the high probability of earthquakes occurring with high magnitude in Tehran on one hand, and the density of structures, violation of construction codes and standards in different parts of the city, and improper distribution of services and facilities as well as dense population in some parts on the other hand has led to increased seismic vulnerability of the city. Therefore, developing a vulnerability map against earthquake for Tehran in order to identify the vulnerable and safe areas in the city, and proper and suitable planning to prevent or decrease the potential effects of earthquake occurrence is of utmost importance.

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3 Methodology and data analysis

3.1 Indicators

As illustrated in Fig. 2 and since the purpose of this study is to investigate the vulnerability against earthquakes with a comprehensive viewpoint, seismic vulnerability must be studied taking all influential factors into account. Thus, after reviewing the literature, regulations, viewpoints and experiences of experts and taking the available data of influential indicators including geotechnical, structural, social and physical distance from needed facilities and away from dangerous ones into consideration, and the main sub-indicators are extracted as follows:

3.1.1 Geotechnical indicators

One of the main and most influential factors which increase the cities' vulnerability during an earthquake can be the geotechnical features of the scope. So by studying and investigating the geotechnical specifications of an area we can gain useful data on the possibility of earthquake and its magnitude as well as spatial data of affected areas. When an earthquake occurs, the released energy is spread inside earth in the form of elastic waves. The acceleration due to strong ground motion in each site depends on a complex combination of earthquake's magnitude, duration, frequency content, the distance between the earthquake's hypocenter and site, soil condition in the scope, etc. Thus, one of the important criteria while designing the structures, and also the main reason for the damages on the buildings, is the peak ground acceleration while an earthquake occurs (Ghodrati Amiri et al., 2010; Babayev et al., 2010; Armaş, 2012; Moradi et al., 2013; Panahi et al., 2014). In Iran, the peak ground acceleration which has destroyed or damaged the structures is between 0.1 g (Golbaf earthquake, 1981) and about 1 g (Zanjiran, 1994; Bam, 2003 on the west-east component, Jafargandomi et al., 2004). On the other hand, earth's slope is another geotechnical factor that must be taken into consideration; since it is one of the influential factors in the instability of steep slopes and landslide occurrence in alluvial and sand soil especially under the structures' foundation while an earthquake occurs (Keefer, 1984; Plakfer and Galloway, 1989; Harp and Wilson, 1995; Jibson et al., 2000; Lee and Talib, 2005; Lee and Pradhan, 2006; Jibson, 2007; Mahdavifar et al., 2002; Safari and Moghimi, 2010; Sarvar et al., 2011). This issue can lead to destruction and an increase in the damages.

3.1.2 Structural indicators

Regarding the fact that many structures in Tehran are quite old and constructed by traditional methods, and also because most newly-constructed structures have violated the construction codes and regulations (BHRC: Building and Housing Research Center, 2005) and there has been inconsistent application of building regulations, the structures are quite vulnerable to earthquake. The proof of it can be understood easily by a glimpse at the earthquakes which have happened during the last few decades in Iran. Therefore, considering the studies done and regarding the limitation of accumulated data in Tehran, using the structural factors such as: type of buildings per census units (structure and building materials), age of buildings, and density of buildings per census units can have determining role on seismic vulnerability (Tavakoli and Tavakoli, 1993; JICA: Japan International Cooperation Agency and CEST: Center for Earthquake and Environmental Studies of Tehran, 2000; Cutter et al., 2003; Chakraborty et al., 2005; Ebert and Kerle, 2008; Ghayamghamian and Khanzade, 2008; Ebert et al., 2009; Lantada et al., 2009; Ishita and Khandaker, 2010; Şen, 2010; Alinia and Delavar, 2011; Martins et al., 2012; Armaş, 2012; Panahi et al., 2014).

3.1.3 Social indicators

Demographic context of a society during an earthquake occurrence or after it, is very important since these factors have a direct relationship with increase or decrease in tolls and facilitation of relief operations. Unfortunately, during recent years, earthquake experts have not paid enough attention to this issue and not enough studies have

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been conducted on last earthquakes with this viewpoint. Therefore, we studied seismic vulnerability articles with the viewpoint of population as the main issue to resolve this issue and the main sub-indicators extracted are as follow:

1. population density (Chakraborty et al., 2005; Bac-Bronowicz and Maita, 2007; Ishita and Khandaker, 2010; Martins et al., 2012; Peng, 2012; Armaş and Gavriş, 2013).

2. ratio of female population in total population (Fothergill et al., 1996; Granger et al., 1999; Fordham, 2000; Wisner, 2003; Cutter et al., 2003; Haki et al., 2004; Armaş, 2012; Martins et al., 2012).

3. ratio of children (King and MacGregor, 2000; Cutter et al., 2003; Dwyer et al., 2004; Steinführer and Kuhlicke, 2007; Birkmann et al., 2008; Holand et al., 2011; Kuhlicke et al., 2011; Armaş, 2012).

4. ratio of elderly population (King and MacGregor, 2000; Cutter et al., 2003; Dwyer et al., 2004; Steinführer and Kuhlicke, 2007; Thieken et al., 2007; Birkmann, 2007; Reid et al., 2009; Flanagan et al., 2011; Holand et al., 2011; Åström et al., 2011; Rocklöv et al., 2011; Armaş, 2012; Zebardast, 2013).

5. level of education (Buckle, 2000; Cutter et al., 2003; Adger et al., 2004; Haki et al., 2004; Velasquez and Tanhueco, 2005; Schneiderbauer, 2007; Ebert and Kerle, 2008; Holand et al., 2011; Kuhlicke et al., 2011; Armaş, 2012; Martins et al., 2012).

6. employment status (Dwyer et al., 2004; Haki et al., 2004; Bac-Bronowicz and Maita, 2007; Ebert and Kerle, 2008; Holand et al., 2011; Kuhlicke et al., 2011; Zebardast, 2013).

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3.1.4 Indicator of physical distance to needed facilities and away from dangerous facilities

One of the infrastructural influential factors in cities is the access of residential and populated areas to medical care facilities, open spaces, road networks, etc. Studies show that in urban societies not all residents have equal access to urban facilities and there may be great differences between the distribution of facilities in different areas of the city based on socio-economic characteristics of residential areas, unplanned development of the cities, etc. On the other hand, we can refer to unequal distribution of dangerous facilities inside dense urban fabrics such as gasoline stations, dangerous industrial establishments, high voltage electrical power transmission lines, etc. which sum of all these reasons lead to an increase in vulnerability and financial and physical tolls while an earthquake occurs. Therefore, with comprehensive and long-term planning to properly locate the urban structures and dangerous facilities, cities' vulnerability can be decreased so much. So, in this paper, having the importance of access to needed facilities and distance from dangerous ones, ten factors which include accessibility and distance to open spaces (parks and barren areas), road network, police stations, fire stations, hospitals, disaster management centers, and distance from gasoline stations, high voltage electrical power transmission lines, gas pipelines and danger-prone industrial establishments have been taken into account to investigate the seismic vulnerability of Tehran metropolitan (Rashed and Weeks, 2003; Servi, 2004; Altan et al., 2004; Hellström, 2007; Ebert and Kerle, 2008; Hizbaron et al., 2011; Armaş, 2012; Nan and Hong, 2013).

3.2 Methodology

The combined method of GIS-AHP is a suitable tool for spatial issues including seismic vulnerability of cities. Since a range of qualitative and quantitative indicators must be taken into account to investigate the seismic vulnerability of an area, as Fig. 2 shows one of the main steps to realize this goal is using AHP to consider this indicators

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simultaneously with regard to the importance of each and using GIS to manage, integrate and analyze the data.

AHP originally introduced by Saaty (1977) is a multi-criteria decision-making technique. In fact AHP is a weighted linear summation method in which the weight is gained through pairwise comparison of elements in a level of decision-making. AHP allows the decision-makers to change a complex problem to a hierarchical structure by identifying the elements of decision-making such as goal, criteria (indicators) and alternatives (sub-indicators), prioritization of them and relating them to each other; and to simplify the analysis and decision-making. Generally, AHP has three stages as follows:

1. developing a tree structure for indicators and sub-indicators.

2. pairwise comparison of indicators and sub-indicators and identifying the weight of each.

3. estimation of consistency between judgments and weights.

In fact, in AHP after identifying the influential indicators and sub-indicators (Fig. 2) for determining the weight of each factor, systematic and structured comparison is used. This kind of comparison reduces the conceptual complexity of the problem under investigation and furthermore, the weight of each factor is determined regarding the amount of importance of it as shown in Table 1 that introduced by Saaty (1977). In other words, in AHP, weights show the dominance and intensity of importance of each factor on the other in a level of hierarchical structure.

The most important issue in AHP and weighting the factors is the consistency between judgments and weights. In order to determine it, consistency index (CI) is used as defined by Saaty (2000) below:

$$\mathrm{CI} = \frac{\lambda_{\max} - N}{N - 1} \quad (1)$$

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where λ_{max} is the largest or principal eigenvalue of the pairwise comparison matrix and N is the order of the matrix. Saaty (1980) has identified average random consistency index (RI) according to Table 2 and calculated the consistency ratio (CR) as follows:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \tag{2}$$

So that if CR = 0, the pairwise comparison matrix has complete consistency and if CR > 0.1, the matrix has inconsistency and pairwise comparison must be reperformed between indicators and sub-indicators.

The final weight is gained according to linear adding of given weights to indicators and sub-indicators (according to Eq. 3) and overlaying weighted raster layers on each other.

$$W = \sum_{j=1}^{n} W_j w_{ij} \tag{3}$$

where W shows the weight of each pixel in vulnerability map, W_j shows the normalized weight of each indicator, w_{ij} is the weight of the ith sub-indicator with respect to the jth indicators and n the total influential indicators.

4 Results

Using AHP and determining the importance of each used indicator and criteria in the study, with respect to four main indicators, the results (Figs. 3 and 4) are as follows:

4.1 Geotechnical indicators

Analysis of seismic vulnerability conducted according to geotechnical viewpoint for all over Tehran shows that proximity of the Mosha fault to north and east-north of Tehran and located at a distance of about 36 km away from the north-eastern part of the city and its intersection with the North Tehran fault has put Tehran in the vicinity of the seismic zone of the fault. Other studies reveal that in case the Mosha fault becomes more active, scope of Tehran will experience the PGA of 200 Gal (JICA and CEST, 2000). According to Fig. 3a, in case an earthquake occurs as a result of this fault's movement, the geotechnical vulnerability in parts of districts 4, 1, 3, 6 and 7 (2 %) will be high due to their vicinity to the fault. Yet, 60 % of Tehran will be safe.

Since the North Tehran fault passes through all northern districts of Tehran and a part of residential structures in districts 1, 3 and 4 are constructed on it or its hanging wall, these areas are prone to direct disruption of earthquake fault. The investigations show in case this fault has an activity, the amount of PGA in the northern area will be around 400 Gal. The more we move towards south, the PGA decreases due to distance from the source of earthquake, reaching around 200 Gal (JICA and CEST, 2000). The studies have also shown that the slope changes from 30 to 0° from north towards south. This makes northern area structures more instable. Therefore, according to Fig. 3b, 12 % of city scope has a high geotechnical vulnerability; being mostly in north of Tehran and near the active North Tehran fault. On the other hand, districts 22, 21, 5, 2, and 9 (16 %) are least vulnerable due to decrease in PGA as a result of distance from fault and decrease in probability of downfall of hillsides as a result of decreased slope.

Finally, the existence of the Rey fault and lineaments in south and south-western Tehran shows that southern parts of the metropolitan including districts 20, 18, 15, 17, 11, 19 and 12 (5 %) will experience major damage in case the Rey fault becomes active (Fig. 3c). One reason for this vulnerability is that southern parts of Tehran are not only near earthquake source, but also due to the alluvial nature of these areas and high underground water level, PGA is high there. As a result, geotechnical vulnerability will increase when an earthquake occurs. Yet, in districts 22, 4, 5, 2, 1, 3, 21 and 6 despite high slope in some parts, low PGA and also located on bedrock will decrease vulnerability.

4.2 Structural indicators

Structurally (Fig. 4a) a great part of districts 4, 12, 8, 11, 10, 14, 7, 5 and 13 (19 %) are highly vulnerable. The reason can be separately stated in this way: districts 10, 11 and 12 are the core of the city and very old. The construction time of some structures refer back to Qajar era (over 70 years ago). Districts 7, 8, 13, 14 are host to migrations and districts 4, 5 are villages which became a part of the city as time passed. Thus, masonry (brick and cement block or stone) as well as sun-dried mud brick and wooden structures are found galore, leading to increased vulnerability of these areas. Another point is that these areas are host to people with lower incomes. Thus, structures with cheap and low quality as well as lack of inspection in the area have multiplied the structural vulnerability in the area.

On the other hand, a great part of districts 2, 4, 5, 3, 1, 6, 20, 21 and 22 are less vulnerable since besides the existence of old and traditional areas, because there has been proper space for construction, affluent people have constructed structures in accordance with standard 2800 (BHRC, 2005). The result is newly-built structures constructed with concrete and steel by professional engineers. In addition, low density construction in these areas has helped reduce structural vulnerability.

4.3 Social Indicators

Social vulnerability map (Fig. 4b) and extracted statistics show a considerable part of districts 12, 14, 4, 16, 10, 17, 18, 19, 20 and 8 (15 %) are highly vulnerable. The reason is that due to low income in these areas, the residents live in small houses and population density and the ratio of women to total population is high. Also, the areas are host to migration and are mostly old. As a result, there are a great number of old people in the area and the high rate of marriage has led to increase in birth rate, which in turn leads to existence of a lot of children in the areas.

On the other hand, parts of districts 1, 2, 4, 3, 6, 5 and 7 are among safe ad low-vulnerable areas since the residents have high income and bigger houses which leads to less density of population. Also, new and almost modern context of the neighborhood has included fewer old people. The trend of keeping distance from traditional culture and living a modern life among residents has made them less willing to marry and as a result, having less children.

4.4 Physical distance indicators

Regarding Fig. 4c, the results show that 5 % of Tehran areas are highly vulnerable with spread throughout the city. Yet old fabrics are more vulnerable compared to other parts. The reason for it can be lack of access to freeways, existence of high voltage electrical power transmission lines and gasoline stations near houses, being distant from hospitals and police stations. Also 21 % of Tehran areas has medium vulnerability and 38 % is lowly vulnerable. Also, in districts 5, 4, 2, 1, 22, 3 and 21 (36 %) the amount of vulnerability is considerably very low because of proper road access, ease of access to police stations, hospitals and emergency management centers, and being distant from gasoline stations, high voltage electrical power transmission lines and gas pipelines.

5 Discussion

Tehran is located among a number of seismic faults with the high potential of earthquake occurrence. Its residential areas are highly vulnerable to earthquake due to dense population, the existence of too many structures in areas, and also violation of construction codes. Thus, in case an earthquake occurs, the possibility of a severe damage will increase dramatically. Therefore, developing a seismic vulnerability map is a useful step to take in order to decrease the severity of a major earthquake impact in the area. Since in this way, construction of the vital structures such as hospitals, schools, etc. in highly vulnerable areas can be limited and establishment of vital roads can be banned or subject to observing all earthquake engineering principles, seismic regulations and construction codes.

This study has extracted information layers in the form of geotechnical, structural, social and physical distance indicators according to three scenarios. Then, using AHP and GIS, three vulnerability maps have been developed for Tehran in case an earthquake occurs as a result of movements on the Mosha, North Tehran and Rey faults. The safe and vulnerable areas in each scenario are as follows:

1. The Mosha fault scenario:
   In this scenario, the seismic vulnerability is low due to distance of the fault from Tehran (around 36 km). Thus, as in Fig. 5a, 6 % of the city has high, 16 % medium, 29 % low vulnerability and 34 % is safe. Therefore, with regard to area, districts 12, 4 and 11 have high vulnerability and districts 5, 2, 4, 21, 20, 6, 3, 1 and 19 are safer.

2. The North Tehran fault scenario:
   Regarding the North Tehran fault, the northern part of the city will experience a great deal of damage since the fault is located on the northern margin of the city and a great population resides on the fault or its hanging wall. Therefore, as in Fig. 5b respectively 16, 27 and 28 % of Tehran areas have high, medium and low vulnerability and 14 % are safe. Thus, districts 1, 3, 4, 12, 5, 8, 10, 2 and 11 are highly vulnerable, while districts 20, 6, 16, 4, 14, 19 and 21 are safest.

3. The Rey fault scenario:
   Due to proximity of southern and central areas of the city to the Rey fault and therefore high intensity of earthquake, low quality and strength of structures, existence of old fabrics and dense population, the amount of structural and social vulnerability is very high. But on the other hand in northern areas of the city, vulnerability is low due to better geotechnical, structural and social conditions than central and southern areas. Regarding the results (Fig. 5c) the amount of seismic vulnerability in the scope of Tehran is 10 % with high, 21 % with medium and 27 % with low vulnerability. 27 % is also safe. Thus, districts 12, 11, 10, 18, 17,

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14, 20 and 16 have high vulnerability. Also districts 2, 1, 4, 3, 5, 6, 21 and 22 are respectively among the safest areas.

6 Conclusions

Developing a seismic vulnerability map is one of the most efficient methods for developing cities in seismically active areas. To this end and since in investigating the vulnerability of an environment different and various factors are involved, four factors of geotechnical, structural, social and physical distance must be investigated simultaneously. For realizing this, developing a spatial GIS model and using the proper algorithm for categorization of factors and weighting them according to AHP seem vital. In the paper three scenarios were investigated since Tehran is located in the domain of the three active faults of the Mosha, North Tehran and Rey. To cover the probable damages as a result of each fault's activity, each one is investigated separately with the following results:

1. spatial GIS model is a proper tool for making database and developing a proper algorithm regarding the relationship among influential factors in determining the seismic vulnerability. The final outcome of this process will be more comprehensive and more close to reality.

2. after identification of each area's vulnerability in each scenario, proper planning and paying close attention to low-cost methods such as increasing the potential for rescue, training, providing facilities for relocating densely populated areas and seismic retrofitting of available structures must be at hand.

3. with a little attention it can be found that in all scenarios, parts of central Tehran including districts 10, 11 and 12 are vulnerable. Since these areas have included business centers, high priority must be given to them.

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4. lack of suitable data regarding districts 15 and 18 has led to failure in process of determining the seismic vulnerability. However, regarding low income of families, immigration and existence of geotechnical hazards in these areas, field studies must be performed to get needed data and to conduct studies to determine seismic vulnerability of these areas.

5. inclusion of factors such as peak ground velocity, surface fault rupture, subsidence, landslide, liquefaction, etc. which has a determining role in seismic vulnerability makes the map closer to reality.

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Table 1. Scale of preference between two parameters in AHP (Saaty, 1977).

Intensity of importance	Degree of preference	Explanation
1	Equally	Two factors contribute equally to the objective
3	Moderately	Experience and judgment slightly to moderately favor one factor over another
5	Strongly	Experience and judgment strongly or essentially favor one factor over another
7	Very strongly	A factor is strongly favored over another and its dominance is showed in practice
9	Extremely	The evidence of favoring one factor over another is of the highest degree possible of an affirmation
2,4,6,8	Intermediate	Used to represent compromises between the preferences in weights 1, 3, 5, 7 and 9
Reciprocals	Opposites	Used for inverse comparison

Table 2. Random inconsistency indices (RI) for $n = 1, 2, \ldots, 12$. (Saaty, 1980 and 2000).

N	1	2	3	4	5	6	7	8	9	10	11	12
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54

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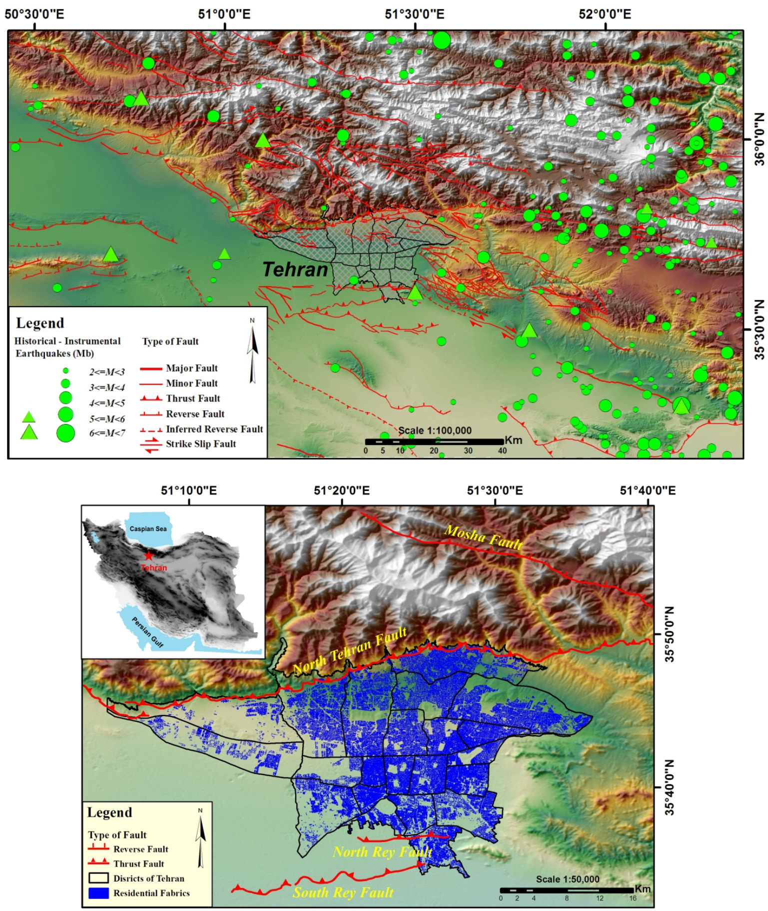

Figure 1. The Study area and the distribution of historical and instrumental earthquakes up to 100 km away from Tehran city.

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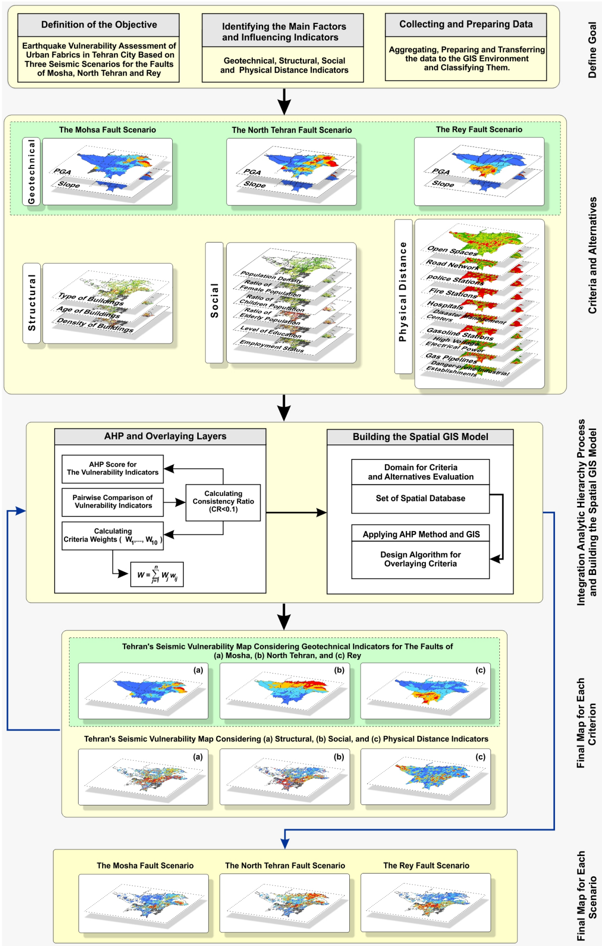

Figure 2. The process of seismic vulnerability assessment using AHP technique.

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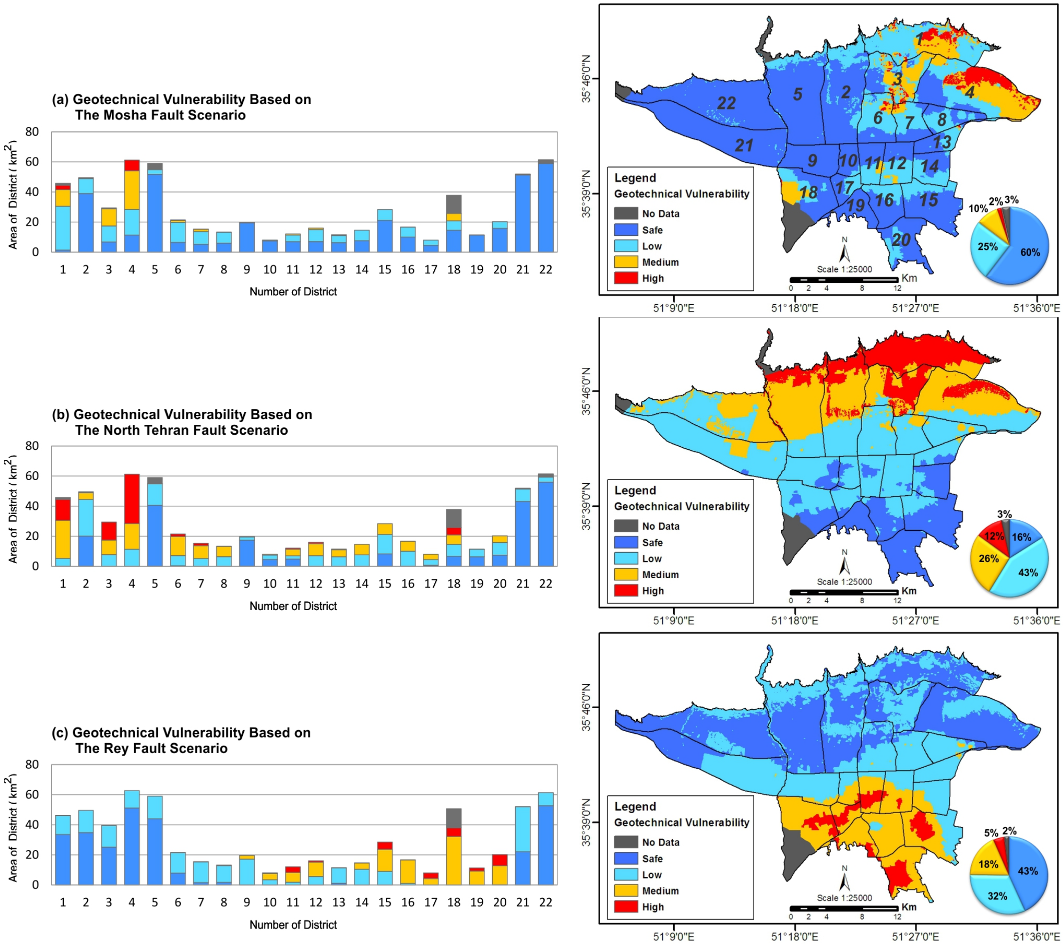

Figure 3. Tehran's seismic vulnerability map considering geotechnical indicator for the faults of **(a)** Mosha, **(b)** North Tehran, and **(c)** Rey.

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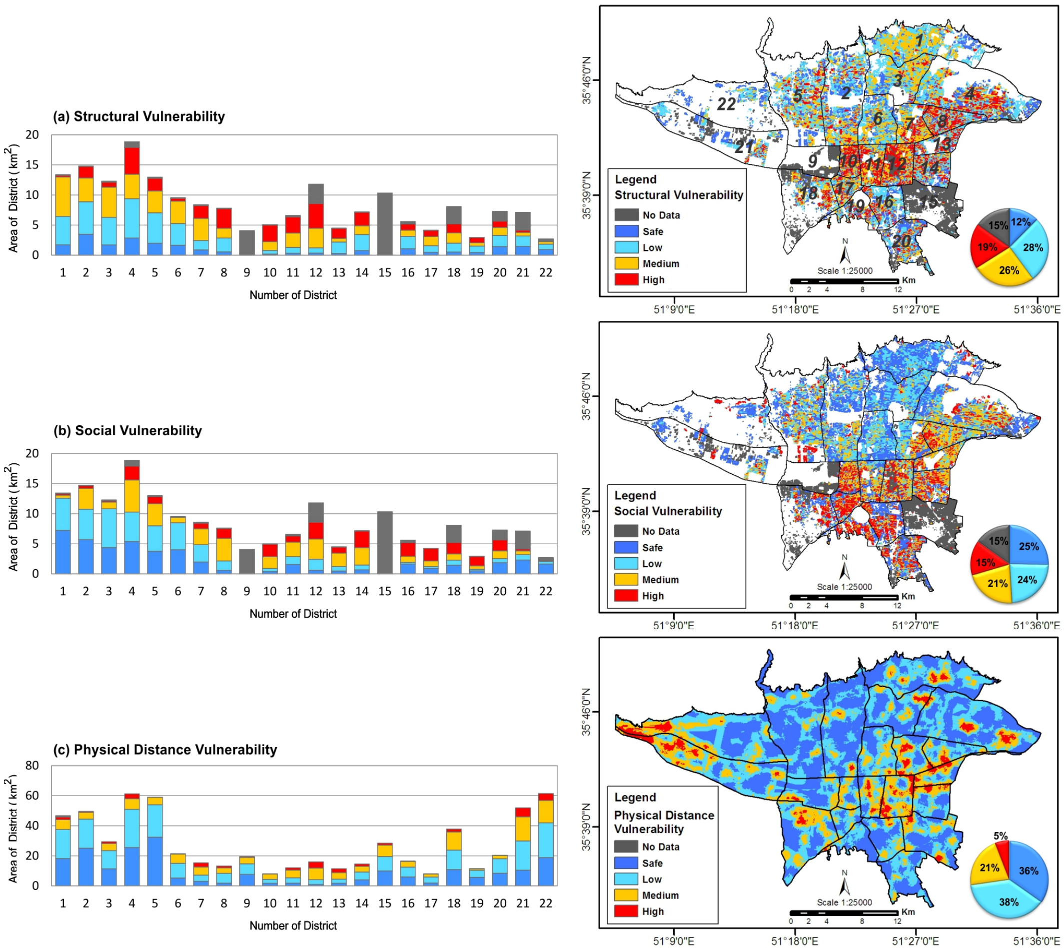

Figure 4. Tehran's seismic vulnerability map considering **(a)** structural, **(b)** social, and **(c)** physical distance indicators.

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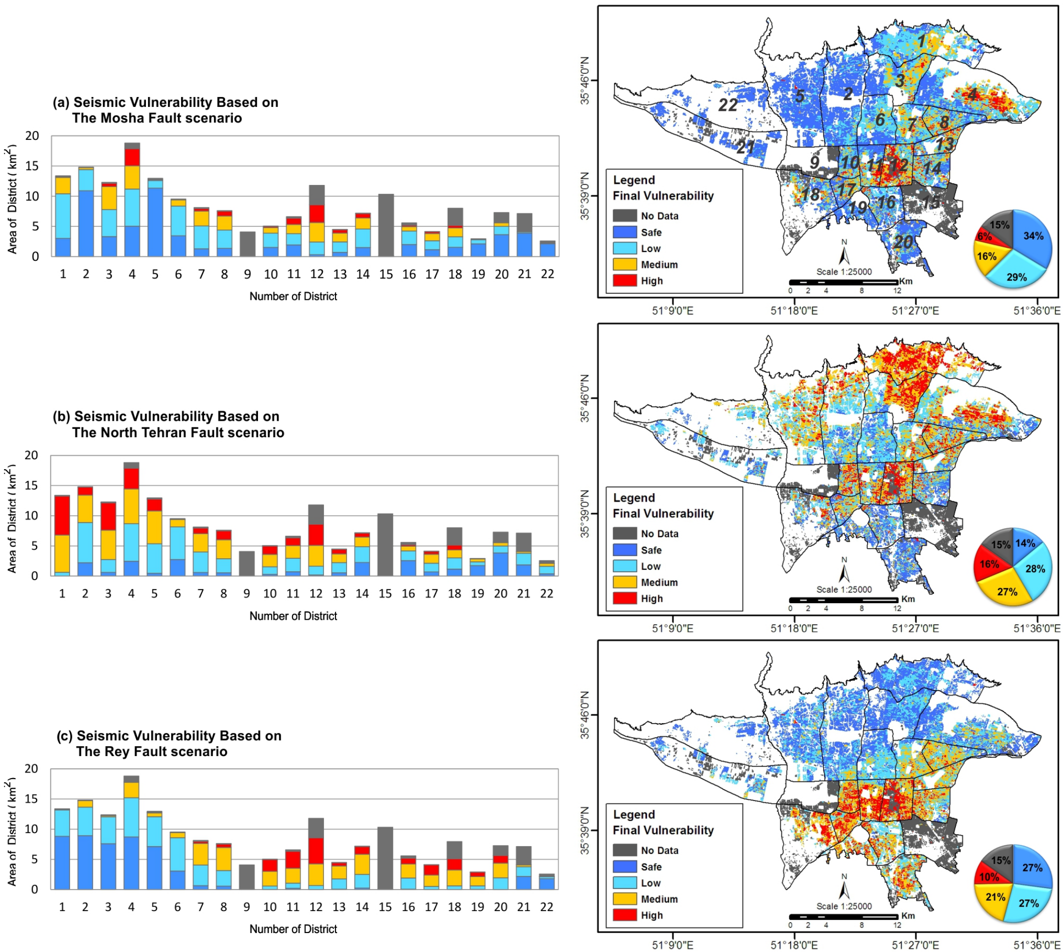

Figure 5. Seismic vulnerability map of Tehran related to three scenarios of **(a)** the Mosha, **(b)** the North Tehran, and **(c)** the Rey faults.

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