



Vulnerability assessment of cities to earthquake based on the catastrophe theory: a case study of Tabriz city, Iran

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Received: 12 September 2019 / Accepted: 30 June 2020 / Published online: 7 July 2020
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Abstract

The present study has been conducted to evaluate the vulnerability of urban spaces to earthquake hazard using the catastrophe theory in the context of geographic information system. In the evaluation method based on the catastrophe theory, the importance of each criterion is calculated using the internal mechanism of system, so subjectivism resulted from decision makers' judgment decreases. This methodology was applied to assess the seismic vulnerability of Tabriz city. During recent decades, this city has developed spatially. Space limitation has caused the development of the city in hazardous locations including the proximity to the Tabriz fault. Considering the seismic potential of the great Tabriz fault and construction density adjacent to this fault, one can say that earthquake is the most important and serious natural hazard in the city. In the current study, important natural, physical, and human variables affecting the level of vulnerability were combined using fuzzy functions of the catastrophe theory. The results indicate the efficiency of this model in seismic microzonation of urban spaces. Results of the seismic microzonation of Tabriz using this model are consistent with field facts. According to the results obtained, a considerable part of the city's built-up lands (more than 35%) is located in the high seismic vulnerability class. Due to the effect of a set of variables such as proximity to the great Tabriz fault, steep slopes, unstable geological formations, marginalization, and high population density and floor area ratio, the vulnerability in parts of the north of the city is very high.

Keywords Microzonation · Vulnerability · Catastrophe theory · Geographic information system · Tabriz

Introduction

There is no common understanding of the vulnerability. Therefore, there are over 25 different definitions of this concept in the literature (Alcántara-Ayala and Goudie 2010). Thywissen (2006) defines the vulnerability as a special dynamic and inner feature of any system, which usually becomes visible during a disaster. Vulnerability can be defined as an internal risk factor of an exposed element to hazard events and corresponds to its intrinsic predisposition to be affected or be susceptible to damage (Barbat et al. 2010).

Earthquake is one of the most destructive natural hazards in the world that causes severe physical, social, and

economic damages. The location of major cities in hazard-prone regions, urbanization, and population growth, and rising wealth measures are the main reasons for high vulnerability of urban spaces to earthquakes (Duzgan et al. 2011).

The prediction of exact location, time, duration, and intensity of earthquakes is not possible. However, probable damages can be estimated. Vulnerability maps of megacities can help efficient postdisaster response to be planned (Moradi et al. 2014). In recent years, the approaches of the vulnerability assessment have shifted towards local analyses. Recognition of most vulnerable areas to earthquakes enables targeted disaster preparedness and response programs to decrease an earthquake's effects (Walker et al. 2014).

Vulnerability includes four dimensions: physical, social, economic, and environmental (Sinha et al. 2014). Therefore, different methodologies have been developed to seismic vulnerability assessment considering various aspects of vulnerability. Several studies have been conducted to investigate vulnerability using multi-criteria evaluation methods. Vicente et al. (2011) discussed vulnerability assessment methodologies. They presented four different vulnerability

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assessment methods (direct, indirect, conventional, and hybrid techniques) and applied a hybrid technique to evaluate the vulnerability of the historic city center of Coimbra. Alinia and Delavar (2011) proposed a new approach, namely, granular computing to overcome uncertainty in seismic vulnerability map. Six physical vulnerability criteria such as earthquake intensity, slope, percentage of more than four-floor buildings, and percentage of building built before 1966 were taken into account as attributes of the objects and urban areas were considered as objects. They compared the results of granular computing with intuitionistic fuzzy and Dempster-Shafer and the findings showed that their results were near to Dempster-Shafer. Armas (2012) used GIS-based multi-criteria analysis to analyze the vulnerability to earthquake in Bucharest. He applied pairwise comparison and ranking algorithms to compute the weights of indicators and criteria. Rashed and Week (2012) assessed the vulnerability to the earthquake by using spatial multi-criteria. They presented a methodology and applied it to a case study from Los Angeles County. The presented methodology combines techniques of multi-criteria evaluation and fuzzy analysis. Mück et al. (2013) assessed building vulnerability to earthquake and tsunami in Cilacap, a coastal city in Indonesia. They used remotely sensed data and Quickbird image. Building height information was derived using a high-resolution DEM. They concluded that there was a good correlation between the survey and remote sensing evaluation. Moradi et al. (2014) assessed physical seismic vulnerability in Tehran. They applied ordered weighted averaging operator (OWA) in order to produce a seismic vulnerability map for Tehran through multi-criteria decision-making (MCDM). Sinha et al. (2014) used the weighted overlay to develop seismic hazard and vulnerability maps and generated seismic risk maps by a combination of these two maps. Rezaie and Panahi (2015) used AHP and geographical information system to study the vulnerability of Tehran to an earthquake under three scenarios. They considered structural, social, geotechnical indicators, and indicator of physical distance to needed facilities and away from dangerous facilities. Results showed that in all scenarios, parts of central Tehran are vulnerable. Armas et al. (2017) introduced a hybrid methodology in order to model seismic vulnerability using both physical and social criteria in Bucharest. The results indicated two major causes for the high vulnerability of the city. Moradi et al. (2017) proposed a new model for seismic vulnerability assessment by using Choquet integral and game theory and assessed seismic vulnerability of Tehran. The proposed model uses fuzzy measures instead of layer weights to take into account positive or negative interaction among criteria. Alizadeh et al. (2018) considered structural, geological and geotechnical data to analyze the seismic vulnerability of residential buildings in Tabriz city. Weights of criteria and the alternatives of each criterion were calculated

using analytic hierarchy process (AHP). The results revealed that the geotechnical factor has the highest contributions to the seismic vulnerability assessment of residential buildings. Zheng et al. (2020) used modified vulnerability index method (VIM) to evaluate seismic risk in Jiangyong, China, in 6369 buildings. They concluded that the applied index shows that there is a strong relationship between distribution of building vulnerability to earthquake and the amount of economic loss. On the other hand, it indicates response of buildings to earthquake.

In GIS modeling, weighting is used in order to get the relative importance of one criterion over the other. Weighting methods are mainly classified into two groups: subjective and objective methods. In subjective weighting methods, the weights are assigned according to the knowledge and judgment of decision makers. On the other hand, objective weighting methods uses mathematical models to assign weights (Ahmed et al. 2015). Analytical hierarchy process (AHP), weighted linear combination (WLC), weighted aggregation method, and weighted sum model (WSM) are some objective weighting approaches. In objective weighting methods such as AHP or fuzzy AHP, the importance of the indicator is divided into certain grades. Therefore, such methods are criticized for its inability to avoid subjectivity and to incorporate the inherent uncertainty (Su et al. 2011). In the present study, in order to reduce uncertainties in multi-criteria decision-making approaches, the catastrophe theory-based method was used in the framework of geographic information system. This method was used to assess spatial vulnerability of Tabriz city, northwest of Iran, to earthquake.

The catastrophe theory has been used in different fields such as groundwater potential (Ahmed et al. 2015; Sadeghfam et al. 2016; Al Abadi and Shahid 2015), land ecological security (Su et al. 2011), water security (Xiao-jun et al. 2012; Yang et al. 2012), water pollution (Wang et al. 2011) vulnerability to floods (You and Zhang 2015) assessment of flood hazard risk (Li 2011) landslide evolution (Tao et al. 2013) and rural infomatization level (Zhang et al. 2010). This method has not been used to evaluate vulnerability to earthquake. Therefore, the primary objective of the current study is to evaluate the vulnerability of Tabriz city to earthquake by using the catastrophe theory.

Study area

Tabriz, the capital city of East Azerbaijan Province, is located in the Northwest of Iran (Fig. 1). Tabriz is the most populated city in the province and one of the most populated cities in the country. With a population of 1.6 million people, this city is the sixth largest city in the country. During the past 20 years, it has grown by about 50% (Siahkali Moradi

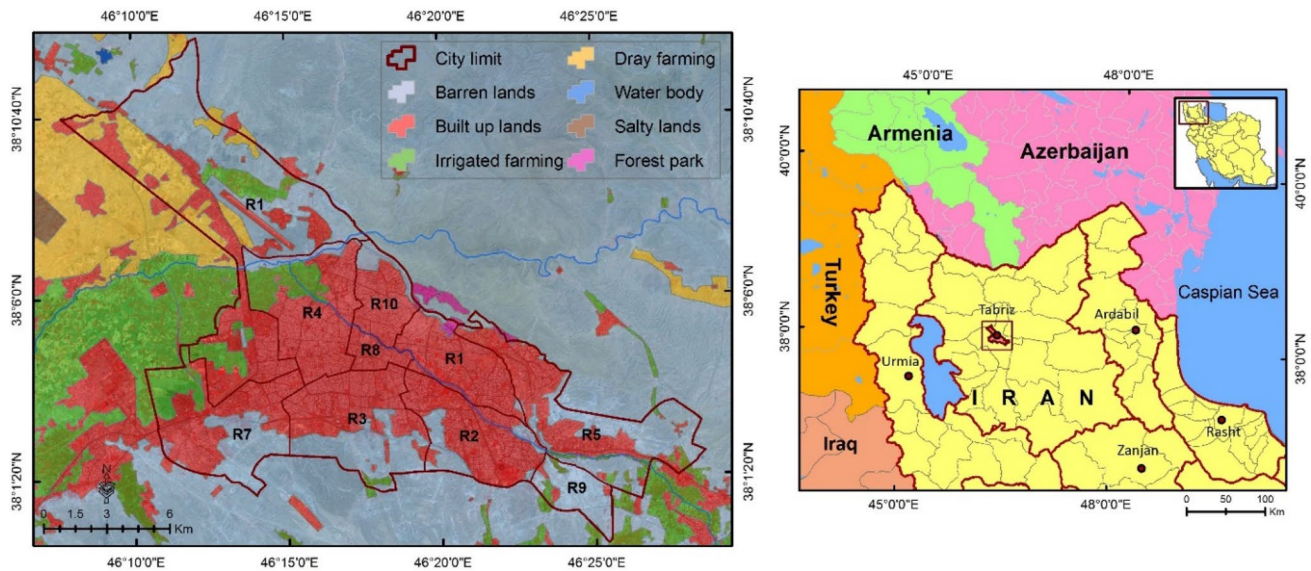


Fig. 1 Location of the study area

et al. 2011). Figure 1 shows the location of Tabriz in the northwest of Iran. In the figure below R1 to R10 are ten municipality regions of Tabriz.

The North Tabriz fault lies at the proximity of the city. Physical development of the city has been along the fault and some of the newly constructed regions such as Eram town, Baghmishe, and northern marginal areas have been constructed near the fault line. This problem due to land and lack of strength of young alluvial in the region can intensify risk and damages resulting from earthquake.

Methodology

Catastrophe theory

Catastrophe theory (CT) is a mathematical model which proposed by Thom (1975). This model studies systems that, under particular conditions, show sudden changes in the steady equilibrium state as a result of small changes in the value of given input parameters. The catastrophe evaluation method does not assign weights to indicators using absolute numbers. It overcomes disadvantages in subjectivity and uncertainty. It aggregates all the indicators when continuous process is optimized, and the system reaches an equilibrium state (Su et al. 2011).

The major aim of the catastrophe theory is to deal with the phenomena of discontinuity. This method uses analytical hierarchy, utility function and fuzzy evaluation to achieve catastrophe fuzzy membership functions by normalized treatment of bifurcation set. Instead of weights assigned by the users, catastrophic fuzzy membership functions

determine the dependency of state variables on control variables. Differences in the initial data dimensions cause incomparability. So, values ranging from 0 to 1 are assigned by the multidimensional catastrophe fuzzy membership functions in order to resolve incompatibility (Ahmed et al. 2015).

There are seven catastrophe models namely, fold catastrophe, cusp catastrophe, dovetail catastrophe, butterfly catastrophe, swallowtail catastrophe, hyperbolic umbilical catastrophe and parabola umbilical catastrophe (Ahmed et al. 2015). These models have been shown in Table 1. In this table, x is state variable and a, b, c, d are control variables.

Methodology based on the catastrophe theory in the framework of geographic information system for the assessment of vulnerability includes four main steps:

Creation of an indicator system

As different control variables have different effects on the state variable, the vulnerability assessment system was classified into several sub-systems such as number of floors, floor area ratio, accessibility to urban open spaces, which define the level of vulnerability. Each sub-system includes some factor or indicator related to vulnerability. It was assumed that the above-mentioned factors act independently, but at the same time interact with each other and control each other inside the system. As a result, these factors strongly affect vulnerability. Each of these indicator systems was investigated separately. In the present study, these sub-systems can be divided into three main groups:

Table 1 Seven types of catastrophe models (Ahmed et al. 2015; Xiao-jun et al. 2012)

Catastrophe model	Control parameters	State variables	Potential functions
Fold	1	1	$V_a(x) = 1/3x^3 + ax$
Cusp	2	1	$V_{ab}(x) = 1/4x^4 + 1/2ax^2 + bx$
Dovetail	3	1	$V_{abc}(x) = 1/5x^5 + 1/3ax^3 + 1/2bx^2 + cx$
Butterfly	4	1	$V_{abcd}(x) = 1/6x^6 + 1/4ax^4 + 1/3bx^3 + 1/2cx^2 + dx$
Oval umbilici point	3	2	$V_{abc}(x, y) = x^3 - xy^2 + a(x^2 + y^2) + bx + cy$
Elliptic umbilici point	3	2	$V_{abc}(x, y) = x^3 - xy^2 + a(x^2 + y^2) + bx + cy$
Parabolic umbilici point	4	2	$V_{abc}(x, y) = x^2y + y^4 + ax^2 + by^2 + cx + dy$

1. Structural indicators

Earthquake in areas where buildings are resilient do not cause much damage, but in areas where buildings are not made of suitable materials, losses and destructions will be high. In the current study, due to limited accessibility to data about the type of materials and buildings quality for the whole of the city, only the number of floors of buildings were used.

2. Planning indicators

The role of urban planning and compilation of its criteria is one of the preventive approaches in the reduction of damages that result from an earthquake in cities. Unsuitable location of physical elements and inappropriate urban land uses, inefficient communication network, very dense urban texture, and lack of urban open spaces and their unsuitable distribution, etc., play a major role in damages caused by earthquake to cities. In the present study, the number of the indicators of this sub-system is more than the others. The role of planning in the framework of thematic layers including spatial distribution of fire stations, hospitals, urban texture, accessibility to open spaces, communication networks, population density, and floor area ratio was considered.

3. Geological indicators

Considering the physical characteristics of a region such as faults, topographic condition, and planning based on it is one of the prevention ways of urban spaces vulnerability to earthquake. Lack of attention to these subjects will damage, in spite of principled construction. In this regard, physical variables of Tabriz such as distance to great north Tabriz fault, lithology, and slope were considered for the vulnerability assessment of urban spaces.

Normalization of indicators

As the range and unit of main data are different, it is not possible to use those units for data analysis, so normalization of data is necessary. This process makes the data dimensionless, thus remove inappropriateness of indicators. In the present study, the following equations were used to normalize

the raster layers of each indicator. The equation used for the standardization of "larger the better" indices (Ahmed et al. 2015):

$$x'_i = \frac{x_i - x_{i(\min)}}{x_{i(\max)} - x_{i(\min)}} \quad (1)$$

The equation used for standardization of "smaller the better" indices:

$$x'_i = 1 - \frac{x_i - x_{i(\min)}}{x_{i(\max)} - x_{i(\min)}} \quad (2)$$

where i is the index of attribute, x_i is the original value of i , and $x_{i(\max)}$ and $x_{i(\min)}$ are maximum and minimum values.

Larger values of population density, floor area ratio, number of floors, slope, access to public open spaces and distance to the operating radius of hospitals and fire stations indicators increase the vulnerability of urban spaces to earthquakes. Therefore the equation of "the larger the better" or in other words "the larger the more vulnerable" (Eq. 1) was used in order to normalization of above-mentioned indicators. Conversely, smaller values of indicators including proximity to fault, proximity to hazardous facilities, and granulation of buildings increase seismic vulnerability. Thus, the equation "the smaller the better" or "the smaller the more vulnerable" (Eq. 2) should be applied to normalize these indicators.

Calculation of fuzzy membership function and multi-criteria decision-making based on the catastrophe theory

Catastrophe progression of each control variable can be calculated using the initial fuzzy subordinate function based on the normalization equations. During the calculation process, two principles are applied: Complementary and non-complementary. Non-complementary principle means that control variable of a system, such as a , b , c , and d cannot be replaced with each other. So, while finding the state variable of x by using the normalization formula, the lowest value of the state variable is corresponding to the control

Table 2 Catastrophe fuzzy membership function (Cheng et al. 1996)

Control variable	State variable	Name	Normalization formula
2	1	Cusp	$x_a = a^{1/2}$ and $x_b = b^{1/3}$
3	1	Swallowtail	$x_a = a^{1/2}$ and $x_b = b^{1/3}$ and $x_c = c^{1/4}$
4	1	Butterfly	$x_a = a^{1/2}$ and $x_b = b^{1/3}$ and $x_c = c^{1/4}$ and $x_d^{1/5}$
5	1	Wigwam	$x_a = a^{1/2}$ and $x_b = b^{1/3}$ and $x_c = c^{1/4}$ and $x_d^{1/5}$ and $x_e^{1/6}$

variables, i.e., $x = \min \{x_a, x_b, x_c, x_d\}$ is selected as the total state variable of the system. On the other hand, complementary principle implies that control variables are complementary, so that each of them tend to reach the mean value, i.e., $x = \{x_a, x_b, x_c, x_d\} / 4$ (Ahmed et al. 2015).

In the present study, complementary principle was used in order to calculate the catastrophe progression of each control variable. Catastrophe fuzzy membership for each indicator is calculated according to Table 2.

In order to determine the type of catastrophe function, Jenks optimization method (Jenks 1967) was used. In this method, break points are determined based on the groups which have similar value and maximum difference with other groups. Jenks optimization method is a method for data clustering which determines the optimum layout of values in the different classes. This method wants to find the minimum deviation of mean from the class mean, whereas it maximizes the deviation of each class from averages of other classes. Therefore, it decreases the variance between classes and maximizes the variance among classes.

Integration of data and spatial vulnerability assessment of Tabriz to earthquake hazard

After weighting each indicator during the previous stages, related layers were combined using geographic information system

$$\text{Vulnerability: } \sum_{i=1}^{11} w_i \times \text{layer}_i \tag{3}$$

here w_i is the weight of each layer and layer_i is the corresponding normalized raster layer.

Most of the geographic information system soft wares has the ability to overlay raster layers. In this regard, in order to overlay the layers affecting the seismic vulnerability of Tabriz city, first the weights obtained from the catastrophe theory were multiplied to the corresponding normalized raster layers; thus, the weighted raster layers were obtained. Finally, the weighted raster layers were added together. In the resulted raster layer, larger values of each pixel indicate higher seismic vulnerability.

Discussion

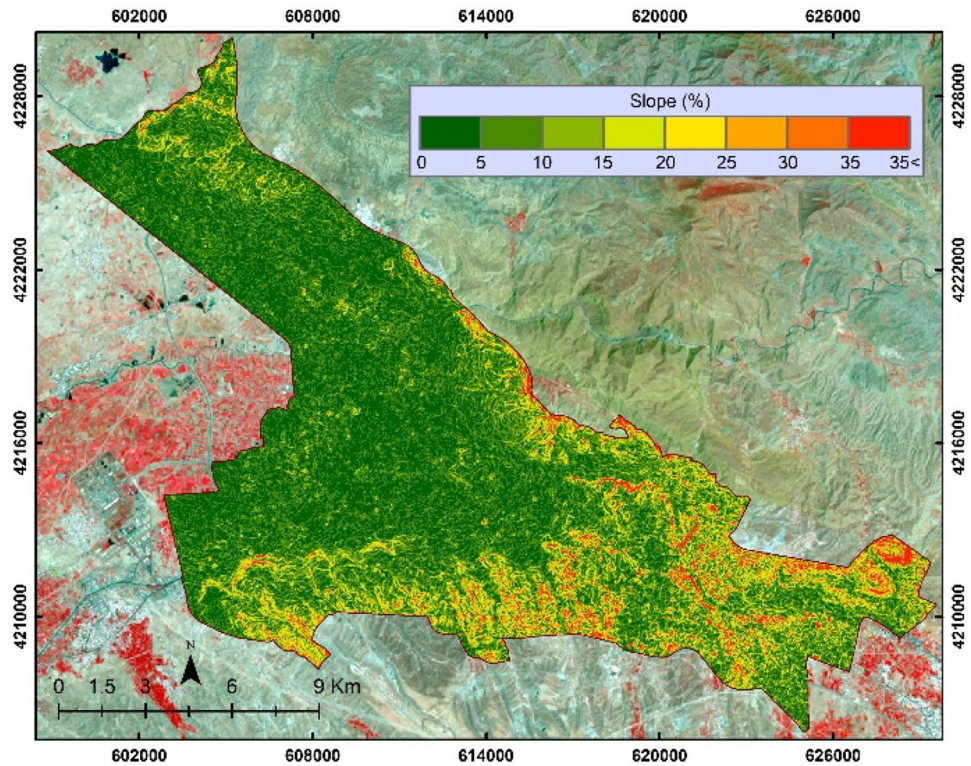
In order to assess the vulnerability of Tabriz to earthquake hazard using the catastrophe theory, system of Tabriz was classified into several sub-systems. Each subsystem includes some assessment indicators. In this research in order to decrease subjectivism, fuzzy membership function frameworks, catastrophe theory, and Jenks optimization method are integrated with each other in a geographic information system. In order to determine the type of catastrophe model, Jenks optimization and the difference between the real and numerical mean of data were used. According to this method, sub-system can be considered as fold (one indicator), cusp (two indicators), swallowtail (three indicators), butterfly (four indicators), and wigwam (five indicators). The data of each indicator related to one sub-system were normalized by using the related catastrophe model to obtain the corresponding fuzzy membership function. This process was repeated to achieve fuzzy membership functions for all sub-systems. Spatial distribution of the study’s subsystems in Tabriz city is briefly considered.

Slope of the city

Slope is one of the effective factors in the level of housing and urban facilities’ vulnerability to natural factors such as earthquake. Slope map of Tabriz was derived from ALOS PALSAR DEM¹ with 12.5-m resolution (Fig. 2). The general direction of slope in Tabriz is south–north and east–west based on the trend of reliefs (Sahand volcano and Eynali Mountains) and the direction of surface water (Aji Chay and Meydan Chay rivers). Considering the relative difference in the city’s elevation, different levels of slope have been formed, but it mainly includes low slope lands. However, parts of Eynali mountains slopes and Meydan Chay valley have slopes greater than 30%. Flatlands (lower than 5%) cover 38% of the city’s area. Municipality regions 4, 6 and 8, which are located in the central and western parts of the city (Fig. 1), have the highest amount of low slope lands. On the other hand, 3% of the lands in the city have slope higher than 30%. In fact,

¹ <https://vertex.daac.asf.alaska.edu/#>.

Fig. 2 Slope map of the study area



lack of topographic limitations in the west and southwest of the region has led to the physical development of the city in these zones. Although the major part of the city has been developed on the lands which have gentle slope (0–5%), in recent years, physical development of the city has occurred on the steep lands in the north of the city. The potential for slope instability in these lands is high. Therefore, these parts of the city are vulnerable to mass movements, too. Slope instabilities are considered as one of the secondary consequences of earthquakes. Totally, Tabriz has 631 ha rough lands with slope more than 30%, which is 3% of the city's total area. These lands, except regions 4 and 8, are scattered in the other regions of the city. The majority of steep lands are located in region 5, with the approximate area of 255 ha. Because of the special geographical location in the eastern part of the city where includes the Eynali Mountains and Meydan Chay valley, this region has steep lands. In spite of being steep, during the recent years, the major physical development of the city has occurred in this region (Fig. 3).

Distance to fault

Existence of an active and great fault known as the North Tabriz Fault which is one of the great tectonic lineaments

of the Iran and passes across the northern half of the city, makes Tabriz city as one of the most hazardous settlement zones. In this region, the majority of installations and facilities of the city such as the international airport have been located.

Considering different seismic features in the north and south of Tabriz, the fault of Tabriz is divided into the northern and southern part, the surface effect of the northern part starts from the north of Tabriz and in the north of Tabriz airport is separated into branches and create very specific fault scrap. The general trend of Tabriz fault is NW–SE and its slope has been reported to be close to right. Approximate length of this fault is 180 km and the average rate of slide is 3 mm per year. Currently, because of the physical development of Tabriz, the fault of Tabriz is considered as one of the city's neighborhoods and Bagh Mishe, Yousef Abad and Eram towns have been constructed on the major trend of Tabriz north fault (Fig. 4). The map of distance to fault has been shown in Fig. 3. Geological map at 1:100,000 scale of geological survey of Iran was used in order to derive lithology and fault map.

The length of Tabriz fault from Sofian in the northwest to Bostanabad in the southeast of the city is 97 km. According to length-magnitude equations (Nowroozi 1985; Mohajer-Ashjai and Nowroozi 1978; Ambraseys and Melville 1982),

Fig. 3 Distance to fault

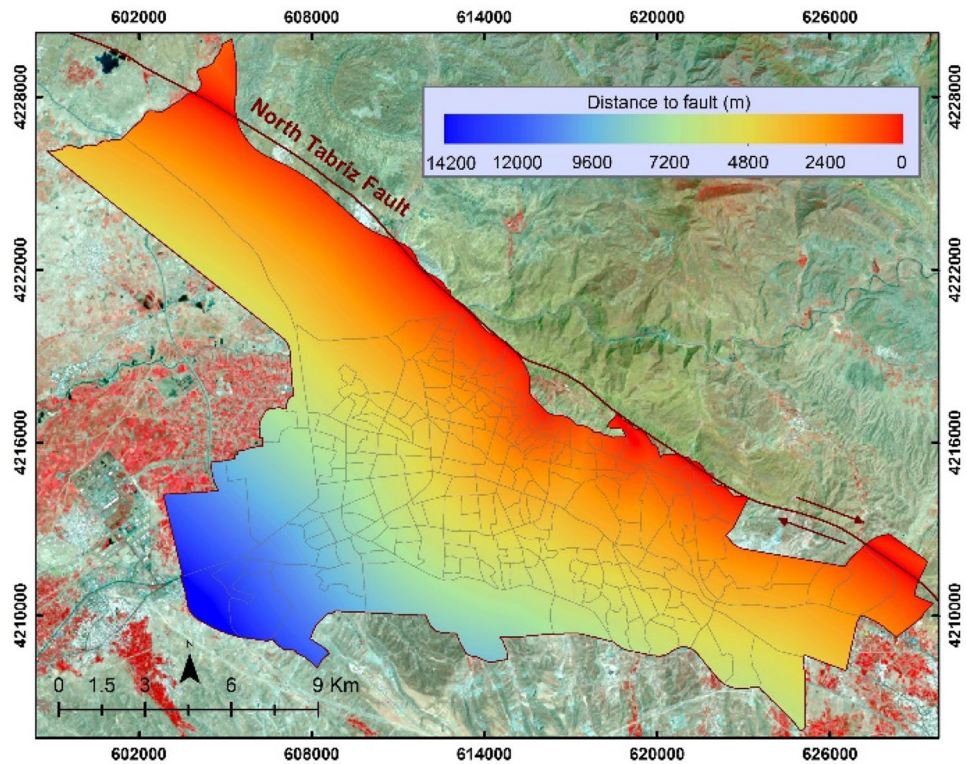


Fig. 4 The great North Tabriz fault crossing from the vicinity of Tabriz city



the Tabriz fault has the potential for producing earthquakes between 6.7 and 7.1 magnitudes on the Richter scale. Indeed, various studies (e.g. Berberian and Arshadi 1976) show that during the history, Tabriz city have been destroyed by severe earthquakes several times, but have been reconstructed due to the special strategic location and fertile agriculture lands. The most intense earthquake of Tabriz with a magnitude of 7.7 on Richter scale occurred in 1780. The casualties of this earthquake have been reported between 40,000 and 70,000 people (Berberian and Arshadi 1976) (Figs. 5, 6).

Lithology of the city

In fact, geological and seismological information about a region are a base for the prediction and simulation of expected earthquakes. Based on experiences gained from earthquakes occurring in different parts of the world and the investigation of the main reasons for damage to buildings, most of the experts believe that damages to buildings depend on the land structure. Therefore, lithological conditions are one of the most important environmental parameters in earthquake occurrence (Shah et al. 1991). In fact, different ingredients of the earth such as bed rock, gravel, sand,



Fig. 5 Marginal part of Tabriz city in the vicinity of Tabriz fault



Fig. 6 Tower construction in the vicinity of Tabriz fault and on unstable geological formations

silt, and mud have different responses to earthquake waves. For example, the amount of vibration in sediments may be stronger than bedrock (Keller and Pinter 1996). Thus, land classification in terms of the type of rock and soil is one of the important factors in vulnerability.

Tabriz has a special situation in terms of geological features. In fact, the morphological structure and natural establishment of the city is in such a situation that it has different landforms such as plain, valley, and steep slopes adjacent to mountain. Different morphology of the city is resulted from variety and difference in its stratigraphy structure and other geological characteristics, especially tectonic issues of this region and its relationship with the fault and basic lineaments of earth which have caused different blocks with different nature and structure to form adjacent to each other (Fig. 7).

As the lithology map of the study area shows (Fig. 7), Tabriz has developed on young alluvial and sediments which are related to quaternary period. Alluvial deposits on the plain have different thickness. In a way that, it varies from the minimum of 20 m in the margin of the plain and adjacent parts to foothill to the maximum of 200 m in the west and center of the city. Distribution of these sediments is consistent with physiography and stream network in the city. Except for the flat parts of the plain, the other parts of the city have been located on hard formations or semi-flat to rough geomorphological forms. In fact, the city has a horseshoe or an elliptical loop shape which is open from west to the plain and smooth areas, while in the other parts, it is surrounded by mountains, low elevation foothills, and hilly forms. This situation has caused the limitation of the city's border expansion which encounters topographic barriers. Therefore, the development possibilities and constraints are important in terms of geographic-physical, and environmental problems, especially in the surrounding borders of the city which are developing and new textures. According to the issues mentioned above, Tabriz has mainly been established on loose and unconsolidated formations, so shocks resulting from earthquakes can be intensified.

Some northern and northeastern parts of the city are consistent with marly formation, in some places its layers are sloped (Fig. 6). Consequently, issues arising from slope instabilities, subsidence, and building foundations are one of the most important urban problems in these areas. In some parts the mass movement occurs slowly, and on the other side land subsides. Both events lead to building failures and damage to them. In general, marl formations are highly susceptible to landslide, hence when other conditions, especially the presence of water and prone slopes or vibrations caused by an earthquake are available, they will have a high potential for mass movement. This is more important due to the presence of the great North Tabriz fault in this area and the occurrence of landslide can be considered as one of the most important secondary consequences of the earthquake in this region.

Population density

Population density includes net and gross types. Its calculation shows that region 10 located in the north of the city has the highest net and gross population density. Khalilabad and Qirikh Iki Metir neighborhoods with the gross population density more than 400 people/ha (as the most densely populated urban neighborhoods) lie in this region. Region 1 with a gross population density of 137 people/ha is in the next order. Regions 9, 6, 5, and 7 with a gross population density of 3, 14, 29 and, 45 people/ha have the lowest population density, respectively (Fig. 8).

Fig. 7 Lithology of the study area

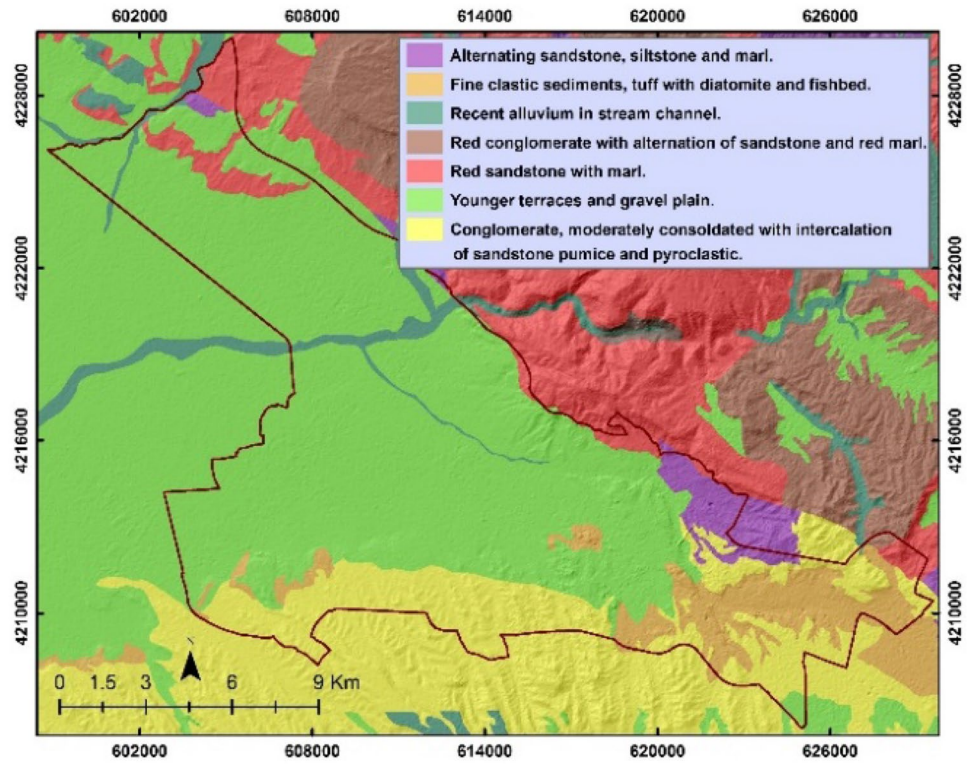


Fig. 8 Population density map of Tabriz

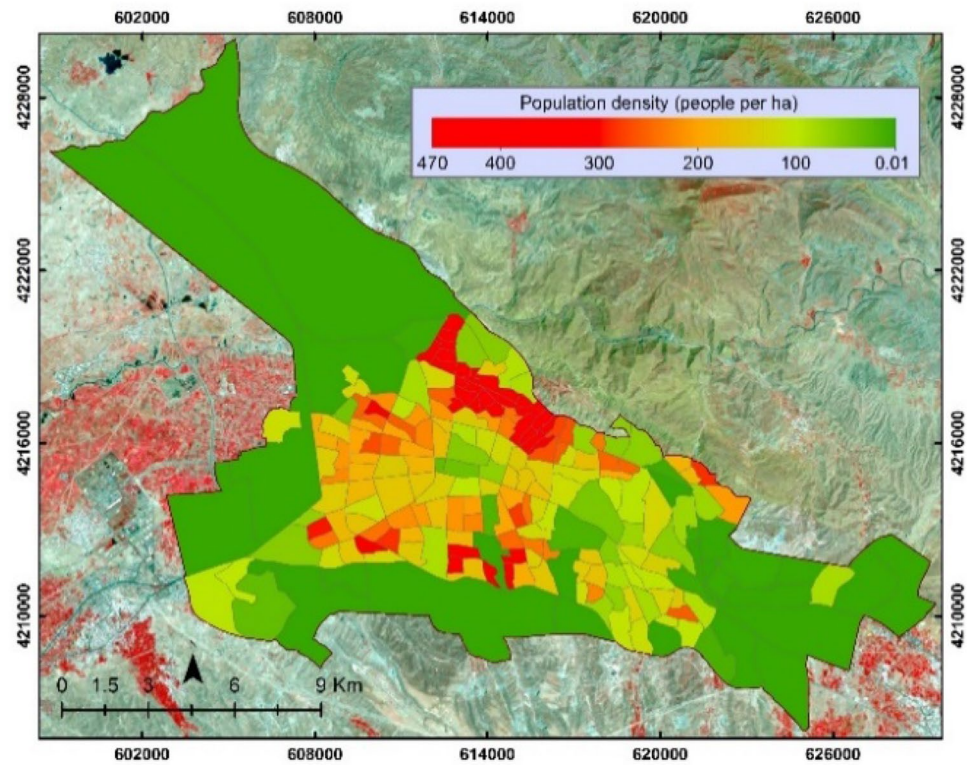
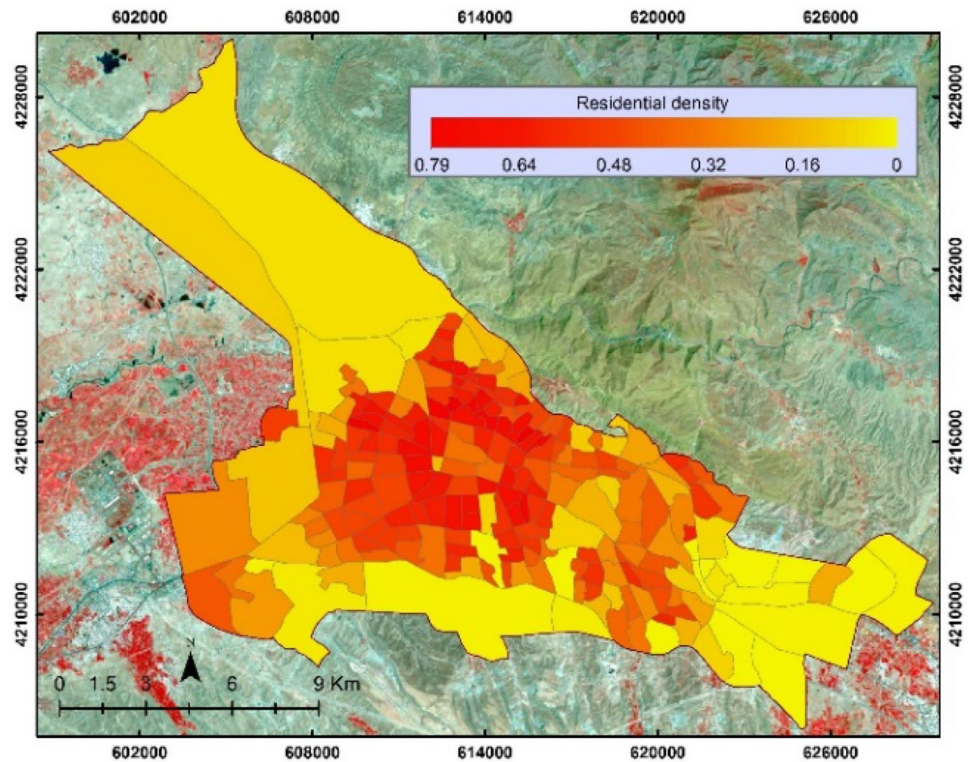


Fig. 9 Spatial distribution of residential density



Comparatively, many neighborhoods of region 10, western neighborhoods of region 1 and some eastern neighborhoods in region 4 with the population density higher than 280 people/ha are the most vulnerable urban regions to earthquake. In some of these neighborhoods, the quality of construction is low, and on the other hand, they have been established in the proximity to the Tabriz fault (Fig. 5).

Floor area ratio

Residential land use is one of the most important land uses in a city. Approximately, 4293.7 ha of Tabriz lands (17.5% of the city's lands) have been dedicated to this type of use. Most of the central parts of the city, which is considered the main core of the city is dedicated to this land use (Fig. 9).

In regions with a high floor area ratio, vulnerability is increased. In the present study, in order to involve construction for determining the urban spaces vulnerability to earthquake, floor area ratio was used. Higher value of this indicator shows the high amount of construction in the region, and vice versa. Therefore, comparatively, the regions which have high amount of construction, because of the limitation of space and high destruction are considered the most vulnerable urban regions. Floor area ratio in the central business district of the Tabriz is high and generally decreases with increasing distance from it (Fig. 10). Therefore, southern neighborhoods of region 10, eastern neighborhoods of region 4, northern neighborhoods of region 3, some western

neighborhoods of region 1, and the whole of the region 8 are considered as the most vulnerable urban spaces because of high floor area ratio and the limitation of space.

Accessibility to fire stations

Security and firefighting services are among the most important urban services for citizens and dwellers of a city. Distribution of fire stations, rescue and relief in the city should be proportional to the vulnerability, population density, time, distance, and accessibility. The area of different urban regions and effect radius of fire stations is considered as a main factor in planning for their location. Therefore, the farther the distance to fire stations, the lower would be the chances to provide timely services to citizens and as a result the vulnerability increase.

There are 20 fire stations in Tabriz, taking 1 fire station located out of the legal limit of the city into account (Fig. 11). Based on the standard distance of 1000 m, the number of existing fire stations in Tabriz is not enough and there is a need for more stations. In the present study, proximity to fire stations, because of fast service providing facilities of these land uses while critical times and unexpected events such as fire, war, earthquake and so on, is considered as an important score and play a main role in the reduction of vulnerability resulting from earthquake. As a result, adjacent regions to fire stations were

Fig. 10 Map of floor area ratio

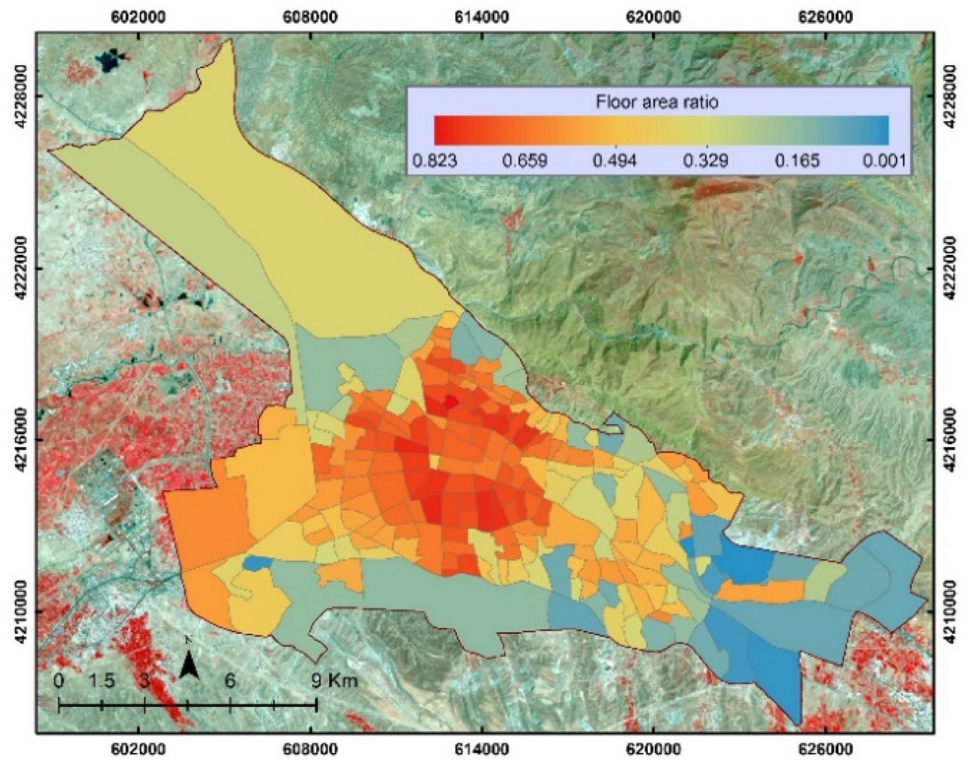


Fig. 11 Servicing area of fire stations in Tabriz

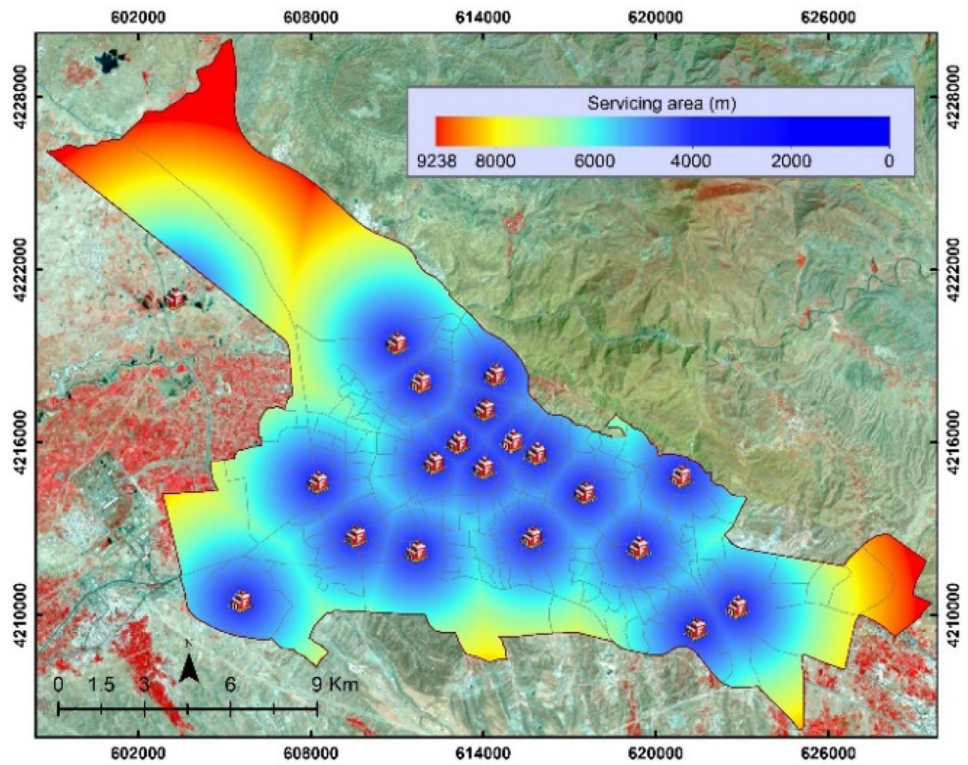
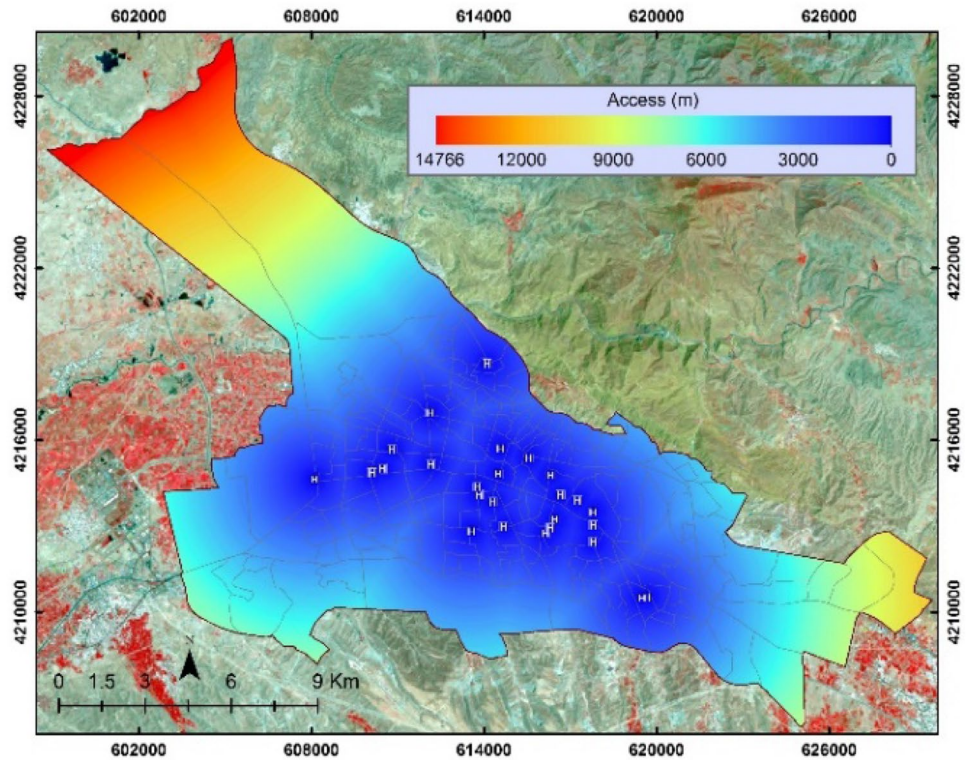


Fig. 12 Map of accessibility to hospitals



considered as points with low vulnerability and as the distance got higher, the vulnerability increased.

Accessibility to hospitals

According to Tabriz University of Medical Sciences, Tabriz has 29 hospitals (Fig. 12) which have been classified in terms of ownership. In this regard, there are 15 public hospitals, seven private hospitals, two military hospitals, two hospitals owned by the social security organization, one charity hospital, one hospital owned by Islamic Azad University, and one hospital owned by the Foundation of Martyrs and Veterans. In terms of activity extent ten provincial hospital, nine regional hospital and ten hospitals have been assigned to abroad regional activities.

The majority of hospitals of Tabriz have been constructed in the central part of the city. Because of the lack of hospital in the eastern, western, and southern part of the city, residents of these parts of the city do not have easy access to health centers. Therefore, while determining the control points, distant points from the city's hospitals were considered as points with the maximum vulnerability and regions adjacent to the existing hospitals were considered as points with low vulnerability.

Hazardous installations

Hazardous installations are referred to the group of facilities which are associated with hazardous substances. These installations can cause other secondary hazards such as fire and explosion. Establishment of land uses having high potential of damage along with other land uses, increases the level of vulnerability. Therefore, the transfer of these installations to out of the city or appropriate buffer zones can be considered as a suitable solution for the reduction of damage (JICA 1999). Promoting the security of hazardous centers and places can be effective in decreasing fires resulting from earthquake. The most important sites include CNG filling stations and town border stations of gas pressure reduction. Cutting gas flow in these centers and stopping gas in the city in severe and moderate earthquakes can be effective in the reduction of hazards, risks, and losses.

Hazardous installations have been distributed throughout Tabriz (Fig. 13). Adjacent regions to these installations are among the most vulnerable urban regions to earthquake. So, thematic layer of distance from hazardous installations, as one of the effective variables of vulnerability of Tabriz, was involved in the final combination of variables and parameters.

Fig. 13 Distance from Hazardous installations

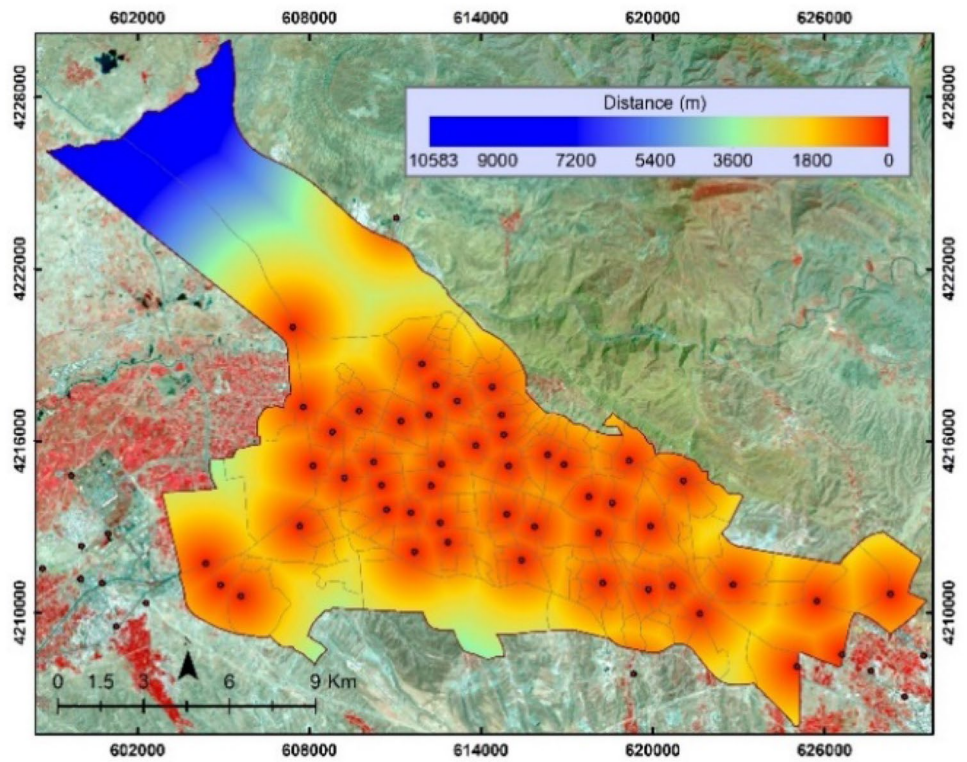


Fig. 14 Map of accessibility to public open spaces in Tabriz

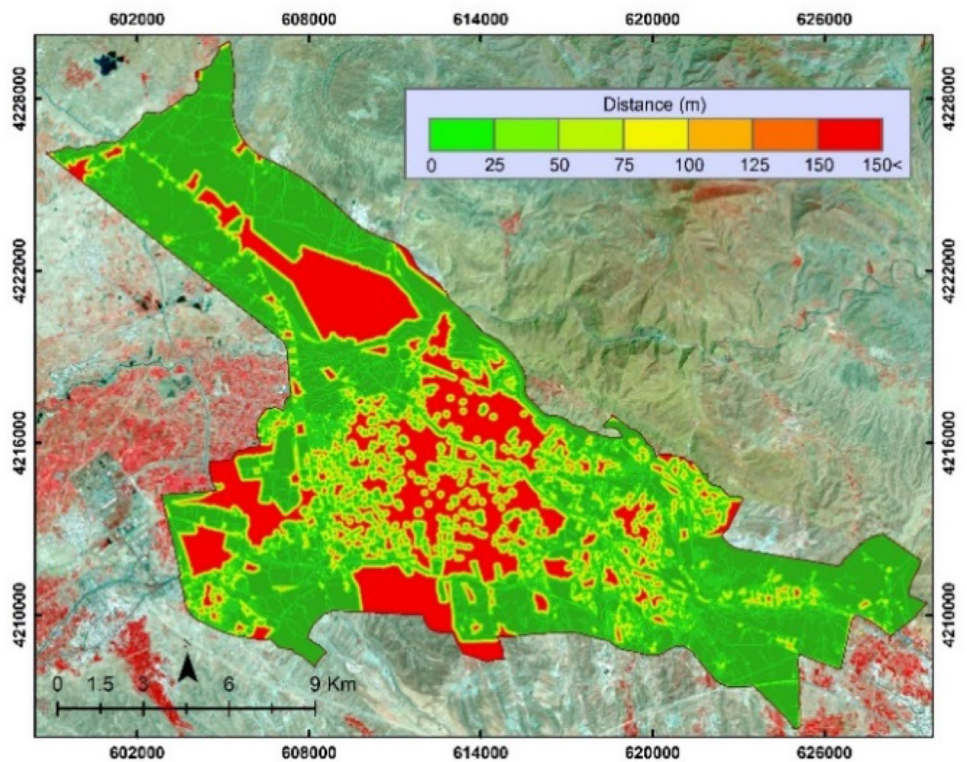
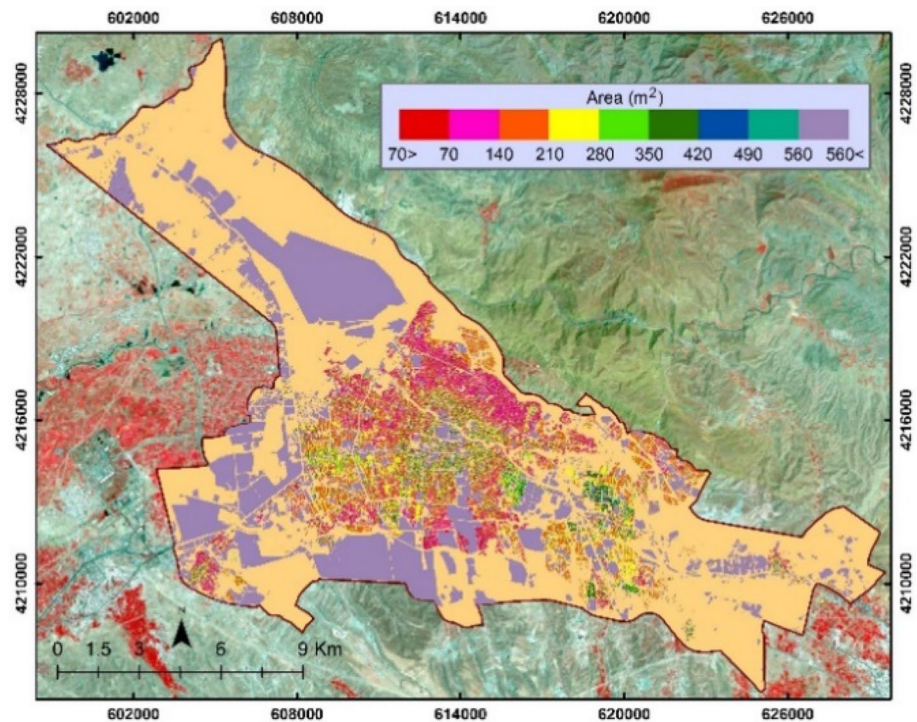


Fig. 15 Urban grain in Tabriz city



Public open spaces

The map of open spaces and access to these spaces in Tabriz (Fig. 14) shows that public open spaces in the outskirts of the city are large in size. While because of high floor area ratio and lack of green spaces and other related land uses, the central parts of the city have limitations in this regard.

Generally, Tabriz is poor with regard to green spaces. The lack of green spaces is very evident in central business district. There is a shortage of green spaces in neighborhoods such as Rezvanshahr, Ghorbani, Mansour, Molla Zeynal, Idehlu and Seylab Ghoshkhaneh. Because of the lack of urban open and green spaces as well as high floor area ratio, these regions have high vulnerability to earthquake. So, having a value close to 1, these regions are the most vulnerable parts of the city to earthquake. Conversely, neighborhoods such as El Goli, Shahid Beheshti town, Eram, Baharan, Laleh alley have high open and green spaces. Therefore, in a similar conditions, they have low vulnerability and were defined as points with zero value. A lack of public open spaces at some outskirts of the city is related to military land uses of these parts.

Urban grain

One of the most important criteria for the determination of vulnerability to earthquake and the increase of its losses is the urban grain, especially residential segments. This criterion is important in terms of some respects. There is an

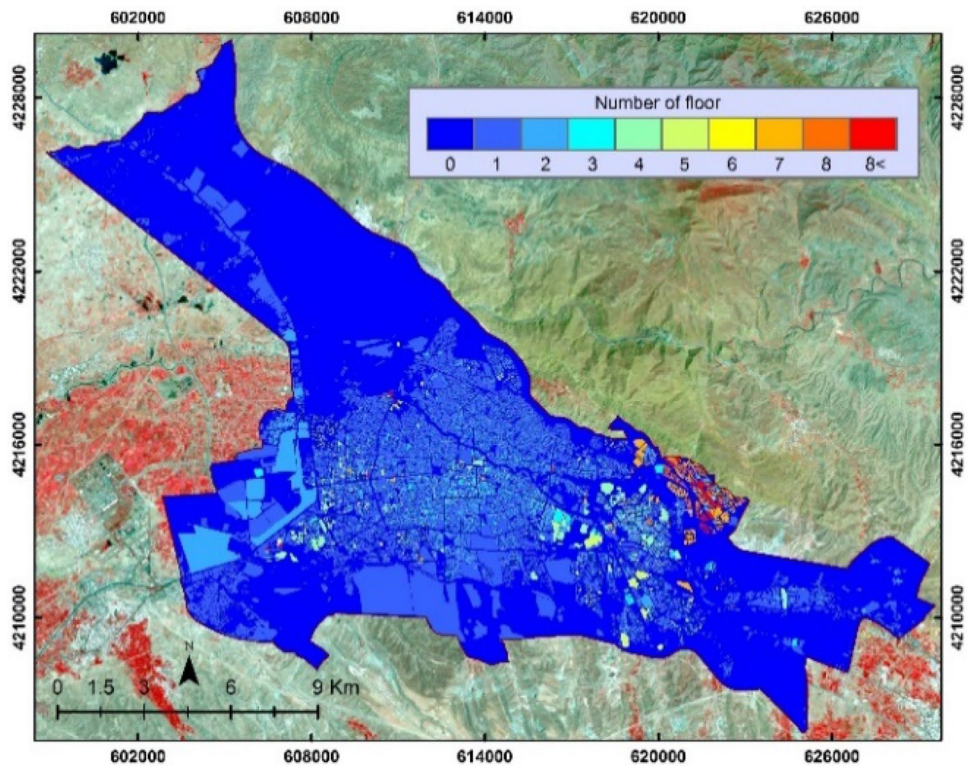
inverse relation between the urban grain and population density. On the other hand, most of the residential segments having low area do not have a suitable construction quality and such textures are more likely to be damaged.

As the map of urban grain in Tabriz show (Fig. 15), fine-grained texture in the parts of north of the city (parts of region 1, 4, and much area of region 10) is considerable, which are more vulnerable, comparatively. Being fine-grained accompanied by other factors such as high population density and floor area ratio, old texture, and proximity to the great fault of Tabriz, increases the vulnerability considerably.

Number of floors

One of the effective internal factors in urban spaces, especially urban buildings vulnerability to earthquake is the number of floors and their height. This indicator shows useful open space for residents and acceleration in services providing. Most of the buildings in Tabriz are one and two storey high (Fig. 16). Most high-rise buildings have been constructed in the east of the city especially Bagh Mishe and Roshdiyeh towns in region 5. Considering great Tabriz fault passing through these regions, vulnerability resulting from the construction of tall buildings increases. Especially, Bagh Mishe and Roshdiyeh towns have been constructed in the buffer of rupture of the Tabriz fault (Fig. 4). Whereas construction is not allowed in the rupture buffer and this area should be allocated for other uses such as public

Fig. 16 Map of the number of floors of buildings (0 indicates barren lands, and green spaces etc.)



green spaces or agriculture. Nevertheless, there is a dense construction in this region in the form of towers and tall buildings.

The integration of indicators by using the catastrophe theory functions

The subsystems and their indicators and the details of the catastrophe weighting method for assessing the vulnerability of Tabriz to earthquake have been presented in Table 3. According to this table, the indicators of distance to fault, population density, floor area ratio, service radius of fire stations, hospitals service area, urban grain, and access to urban open spaces meet the wigwam function. The number of building floors and the slope indicators meet the butterfly model and the distance from hazardous installations and lithology meet the swallowtail function. Strong spatial variability of variables and parameters affecting vulnerability has caused that catastrophe function type of most of the indicators to be wigwam.

Based on the complementary principle, indicators of distance to fault, urban grain, floor area ratio, and population density placed the highest priority, with values of 0.72, 0.72, 0.71 and 0.67, respectively. The indicator of slope and hospital service area with a value of 0.65 and 0.61 are in the lowest priority, respectively. Finally, based on Eq. 3, the data layers were combined within the framework of geographic information system. The final map has

values ranging from 9.47 to 46.44, which is reclassified into five vulnerability classes.

The final result of the combination of thematic layers by using catastrophe theory is shown in Fig. 17. This figure indicates spatial vulnerability of Tabriz to earthquake. In a comparative manner, the map zones the city in terms of vulnerability, considering eleven selected variables. So, it can help identify critical places of the city to earthquake. Generally, the legal area of Tabriz in terms of vulnerability to earthquake was classified into five classes. In fact, considerable part of the main core of the city lies in high and very high vulnerability classes. The other parts have moderate vulnerability. Given the Tabriz fault's seismic potential, physical, human, and environmental conditions of different parts of the city determine the level of vulnerability to earthquake.

The southern strip of Tabriz is one of the regions with low vulnerability. The main reasons are distance to Tabriz fault, low population density and floor area ratio, and access to open spaces. Fifty percent of city's area lies in the low and fairly low vulnerability class. These regions are consistent with urban open spaces such as communication network, parks, bare lands, and agricultural lands. In fact, the main reason for the lower vulnerability of these regions is the low floor area ratio and residential density and as a result low population density and wide open spaces. As a result, considering the high importance of population density and floor area ratio and other variables

Table 3 Details of catastrophe weighting method for integrating vulnerability's effective indicator systems of Tabriz to earthquake

Data layer	Control parameters	Indicators	Mean	Standard deviation	Coefficient of variations	Normalization of mean value	Catastrophe function	Catastrophe fuzzy membership	Priority based on complementary principle	Weight
Distance to fault	$0 \leq \text{Class} 1 \leq 2227$	Very dangerous	1170.8	627.4	0.536	1	Wigwam	1	0.7209	11
	$2227 < \text{Class} 2 \leq 4399$	Dangerous	3318	624.3	0.188	0.795		0.926		
	$4399 < \text{Class} 3 \leq 6849$	Moderately dangerous	5458.6	692	0.127	0.590		0.877		
	$6849 < \text{Class} 4 \leq 9912$	Relatively low danger	8182.5	857.2	0.105	0.33		0.801		
	$9912 < \text{Class} 5 \leq 14,200$	Low danger	11,641.6	1034.6	0.089	0		0		
Population Density	$0 \leq \text{Class} 1 \leq 34$	Very low density	2.42	5.69	2.356	0	Wigwam	0	0.6669	8
	$34 < \text{Class} 2 \leq 108$	Low density	77.79	18.12	0.233	0.226		0.609		
	$108 < \text{Class} 3 \leq 182$	Moderate density	141.95	20.37	0.143	0.418		0.804		
	$182 < \text{Class} 4 \leq 275$	High density	223.67	24.20	0.108	0.664		0.921		
	$275 < \text{Class} 5 \leq 470$	Very high density	335.88	36.37	0.108	1		1		
Number of floors	$1 \leq \text{Class} 1 \leq 2$	Low-rise	1.259	0.438	0.348	0	Butterfly	0	0.6343	5
	$2 < \text{Class} 2 \leq 5$	Medium-rise	3.838	0.75	0.195	0.271		0.647		
	$5 < \text{Class} 3 \leq 8$	Relatively high-rise	7.216	0.503	0.070	0.627		0.89		
	$8 < \text{Class} 4$	Relatively very high-rise	10.761	1.310	0.122	1		1		
Floor area ratio	$0 \leq \text{Class} 1 \leq 0.223$	Very low	0.123	0.056	0.456	0	Wigwam	0	0.712	9
	$0.223 < \text{Class} 2 \leq 0.429$	Low	0.342	0.044	0.129	0.352		0.706		
	$0.429 < \text{Class} 3 \leq 0.575$	Moderate	0.517	0.039	0.075	0.635		0.893		
	$0.575 < \text{Class} 4 \leq 0.688$	High	0.633	0.032	0.051	0.821		0.961		
	$0.688 < \text{Class} 5 \leq 0.823$	Very high	0.744	0.031	0.042	1		1		

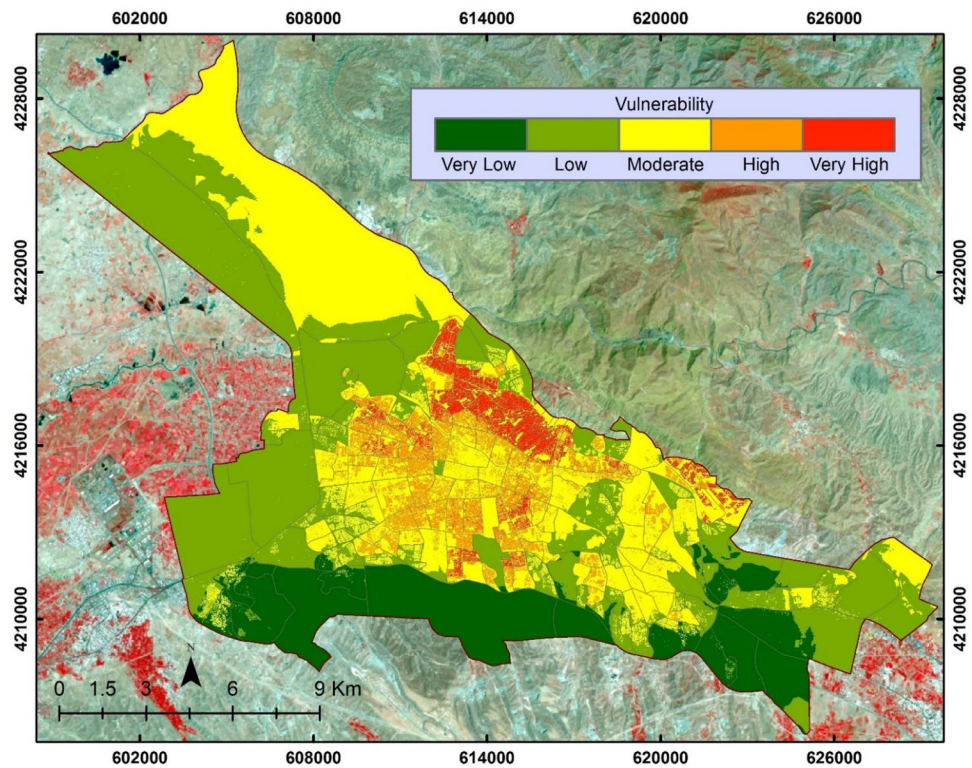
Table 3 (continued)

Data layer	Control parameters	Indicators	Mean	Standard deviation	Coefficient of variations	Normalization of mean value	Catastrophe function	Catastrophe fuzzy membership	Priority based on complementary principle	Weight
Radius of fire station providing	0 ≤ Class 1 ≤ 1304	Very suitable	811.3	312.9	0.386	0	Wigwam	0	0.6601	7
	1304 < Class 2 ≤ 2427	suitable	1815.4	319.5	0.176	0.189		0.574		
	2427 < Class 3 ≤ 3732	Relatively suitable	3002.3	376.1	0.125	0.412		0.801		
	3732 < Class 4 ≤ 5290	Unsuitable	4422.1	461.2	0.104	0.679		0.925		
	5290 < Class 5 ≤ 9239	Very unsuitable	6129.8	782.4	0.128	1		1		
Hazardous installation	0 ≤ Class 1 ≤ 250	Very dangerous	166	59.1	0.356	1	Swallowtail	1	0.6534	6
	250 < Class 2 ≤ 500	Relatively dangerous	386.1	70.6	0.183	0.886		0.960		
	500 < Class 3	Relatively safe	2087.7	2011.1	0.963	1		0		
Hospital service providing	0 ≤ Class 1 ≤ 1000	Very suitable	586.8	249.8	0.426	0	Wigwam	0	0.61	2
	1000 < Class 2 ≤ 2000	suitable	1466.5	287.1	0.196	0.123		0.498		
	2000 < Class 3 ≤ 3000	Relatively suitable	2489.5	289.4	0.116	0.266		0.718		
	3000 < Class 4 ≤ 4000	Unsuitable	3465.4	287.5	0.083	0.403		0.834		
	4000 < Class 5	Very unsuitable	7727.9	3006.2	0.389	1		1		
Texture	5 ≤ Class 1 ≤ 110	Very fine-grained	68.9	25.6	0.371	1	Wigwam	1	0.7205	10
	110 < Class 2 ≤ 181	Fine-grained	149.7	20.1	0.134	0.784		0.922		
	181 < Class 3 ≤ 266	moderate	219.1	23.1	0.106	0.599		0.880		
	266 < Class 4 ≤ 386	Coarse-grained	320.6	33.8	0.105	0.328		0.800		
	386 < Class 5	Very coarse-grained	443.7	48.4	0.109	0		0		

Table 3 (continued)

Data layer	Control parameters	Indicators	Mean	Standard deviation	Coefficient of variations	Normalization of mean value	Catastrophe function	Catastrophe fuzzy membership	Priority based on complementary principle	Weight
Slope	0 ≤ Class 1 ≤ 5	Low	2.86	1.61	0.565	0	Butterfly	0	0.5995	1
	5 < Class 2 ≤ 12	Relatively low	7.82	1.93	0.246	0.186		0.571		
	12 < Class 3 ≤ 20	high	15.32	2.33	0.152	0.467		0.827		
Accessibility to public and open space	20 < Class 4 ≤ 157	Very high	29.52	10.17	0.344	1		1		
	0 ≤ Class 1 ≤ 68	Very suitable	11.2	18.6	1.666	0	Wigwam	0	0.6238	3
	68 < Class 2 ≤ 214	Suitable	125.7	40.4	0.321	0.114		0.486		
	214 < Class 3 ≤ 451	Moderate	303	64.5	0.213	0.292		0.735		
	451 < Class 4 ≤ 806	Unsuitable	598.1	102.2	0.171	0.586		0.899		
Lithology	806 < Class 5	Very unsuitable	1012.2	144.3	0.143	1		1		
	1 ≤ Class 1 ≤ 3	Relatively resistant	1.364	0.495	0.362	0	Swallowtail	0	0.6317	4
	Class 2 = 4	Moderately resistant	4	0	0	0.717		0.895		
	4 < Class 3 ≤ 7	Loose rocks	5.038	0.453	0.09	1		1		

Fig. 17 Spatial vulnerability zonation of Tabriz to earthquake using catastrophe theory



derived from them, these areas are considered as less vulnerable.

Approximately 14% of the total area of Tabriz lies in the high and very high vulnerability classes. Given that the area of the city's built-up lands is about 40%, considerable percentage of these lands in the city (more than 34%) is in high and very high vulnerability classes. Distribution of these zones is impressive, especially in the northwest of the city. This region as a continuous strip covers the western parts of region 1, most part of region 10, and eastern part of region 4. In fact, these zones can be considered the most critical regions of Tabriz. Proximity to the great Tabriz fault, the presence of hilly lands with steep slopes, unstable geological formations especially marl, high residential and population density, high floor area ratio (this region is one of the densest regions in terms of floor area ratio, residential and population density), fine grained building, and lack of urban open spaces have caused that this region to have severe vulnerability to earthquake. If other factors such as marginalization (Fig. 5), old texture, and secondary consequences of earthquake are added to these variables, the level of vulnerability and depth of crisis will be more pronounced.

Conclusion

This research was conducted with the aim of using the catastrophe model in assessment the vulnerability of urban spaces to earthquake hazard. Almost, all of the multi-variate decision-making models are based on subjective weighting and influenced by decision makers' judgment. In the present study in order to decrease subjectivism, the functions of catastrophe theory was used for determining weights of different variables. In this method, the importance of each criterion to the other is calculated through its internal mechanism, therefore the disadvantage of subjectivism decreases greatly. Mathematical foundation, reduction in decision-making uncertainty during weighting process and to some extent in classification uncertainty, consideration of spatial differentiation of variables, the ability to repeat the results by different researchers, high flexibility in the number of variables, and usage in all geographic conditions (physical and human) are the most important advantages of this model. Therefore, it overcomes disadvantages of subjectivity and uncertainty.

In order to evaluate the efficiency of this model in the vulnerability assessment of urban spaces to earthquake, Tabriz metropolis was selected as the case study. Location of Tabriz in the Alpine-Himalayan seismic zone, tensions resulting from the movement of Arabian plate toward Iran and tectonic complexities in this area has made it a hazardous region in terms of seismic. Tabriz has been located in the center of this area and has high population density as well as huge engineering structures. The North Tabriz fault is an active and great one which can produce earthquake with a magnitude of 7 Richter. The historical records confirm it. High density construction in the vicinity of the North Tabriz fault has caused it to be one of the most dangerous fault of Iran. The trend of spatial-physical development of the city in the past, present and with a high probability in the future is in a such a way that environmental threats and hazards will increase. For the seismic microzonation of the city using the catastrophe functions, eleven important natural, physical and human variables effecting the vulnerability were used. Unfortunately, like many cities in developing countries, more spatial data for the city were unavailable, so just the variables used in this study were sufficient. Obviously, more variables can increase the efficiency of the results of the model. In this regard, this approach can lead to seismic zoning of the city, especially in cities that do not have more spatial and non-spatial data, which is very important in the management of earthquake risk reduction. The results indicate the high efficiency of this model and the high vulnerability of the most parts of the city to earthquake. In fact, the combination of a set of variables such as proximity to the north Tabriz fault, unstable geological formations, steep slopes, high population density and floor area ratio, the severe lack of open urban spaces, etc. has caused some parts of the city (especially in the northern parts) to have a high level of vulnerability to earthquake and its secondary consequences. These zones generally include city's marginal parts and old texture. In the event of an earthquake, these regions will become critical focuses of the city. Due to poor financial status of most of the residents of these regions, it seems that the government's involvement in order to increase the strength of buildings and in a long time scale evacuation of parts of the city would be unavoidable.

In the present study, the functions of catastrophe theory have been used to address some of the issues and uncertainties associated with the overlaying of thematic layers in the framework of a geographical information system. There are many spatial or geographical issues that require the integration of variables or the overlaying of thematic layers, including site selection, landslide risk zoning, flood risk zoning, and so on. Thus, the functions of catastrophe theory have the potential to be used in a wide range of spatial subjects. As

mentioned earlier, one of the most important advantages of using the functions of catastrophe theory in overlaying layers is the ability to repeat the results by different researchers, which is very important in spatial analyses.

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