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Multi-Criteria Decision Making (MCDM) Model for Seismic Vulnerability Assessment (SVA) of Urban Residential Buildings

Mohsen Alizadeh [1], Mazlan Hashim [2,*], Esmaeil Alizadeh [3], Himan Shahabi [4], Mohammad Reza Karami [5], Amin Beiranvand Pour [6,*], Biswajeet Pradhan [7,8] and Hassan Zabihi [9]

1 Department of Urban Regional Planning, Faculty of Built Environment, Universiti Teknologi Malaysia (UTM), Johor 81310, Malaysia; alizadeh.mohsen2003@yahoo.com
2 Geoscience and Digital Earth Centre (INSTeG), Research Institute for Sustainable Environment, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
3 Faculty of Business and Economic, Technische Universitat Bergakademie Freiberg, 09599 Freiber, Germany; alizadeh.esmaeil.1985@gmail.com
4 Department of Geomorphology, Faculty of Natural Resources, University of Kurdistan, Sanandaj 15175-66177, Iran; h.shahabi@uok.ac.ir
5 Department of Social Science, Faculty of Humanities and Social Sciences, Payam Noor University, Tehran 4697-19395, Iran; karami_mohammadreza@ymail.com
6 Korea Polar Research Institute (KOPRI), Songdomirae-ro,Yeonsu-gu, Incheon 21990, Korea
7 Centre for Advanced Modelling and Geospatial Information Systems (CAMGIS), Faculty of Engineering and Information Technology, University of Technology Sydney, New South Wales 2007, Australia; Biswajeet.Pradhan@uts.edu.au
8 Department of Energy and Mineral Resources Engineering, Choongmu-gwan, Sejong University, 209 Neungdong-ro Gwangjin-gu, Seoul 05006, Korea
9 Department of Geoinformation, Faculty of Geoinformation and Real Estate, Universiti Teknologi Malaysia, UTM Skudai, Johor 81310, Malaysia; Hassan.zabihi@gmail.com
* Correspondence: mazlanhashim@utm.my (M.H.); beiranvand.amin80@gmail.com (A.B.P.); Tel.: +607-5557694 (M.H.); +82-327-605-472 (A.B.P.)

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Abstract: Earthquakes are among the most catastrophic natural geo-hazards worldwide and endanger numerous lives annually. Therefore, it is vital to evaluate seismic vulnerability beforehand to decrease future fatalities. The aim of this research is to assess the seismic vulnerability of residential houses in an urban region on the basis of the Multi-Criteria Decision Making (MCDM) model, including the analytic hierarchy process (AHP) and geographical information system (GIS). Tabriz city located adjacent to the North Tabriz Fault (NTF) in North-West Iran was selected as a case study. The NTF is one of the major seismogenic faults in the north-western part of Iran. First, several parameters such as distance to fault, percent of slope, and geology layers were used to develop a geotechnical map. In addition, the structural construction materials, building materials, size of building blocks, quality of buildings and buildings-floors were used as key factors impacting on the building's structural vulnerability in residential areas. Subsequently, the AHP technique was adopted to measure the priority ranking, criteria weight (layers), and alternatives (classes) of every criterion through pair-wise comparison at all levels. Lastly, the layers of geotechnical and spatial structures were superimposed to design the seismic vulnerability map of buildings in the residential area of Tabriz city. The results showed that South and Southeast areas of Tabriz city exhibit low to moderate vulnerability, while some regions of the north-eastern area are under severe vulnerability conditions. In conclusion, the suggested approach offers a practical and effective evaluation of Seismic Vulnerability Assessment (SVA) and provides valuable information that could assist urban planners during mitigation and preparatory phases of less examined areas in many other regions around the world.

Keywords: analytic hierarchy process AHP; GIS; seismic vulnerability assessment (SVA); residential buildings; geotechnical vulnerability; structural vulnerability

1. Introduction

Earthquakes are among the global natural catastrophes that cause severe physical, social, and economic destruction annually. The seismic risks in metropolitan regions are described through the complex terms 'seismic hazard' as well as 'seismic vulnerability' [1,2]. Studies on seismic hazard analysis (SHA) serve as a conceptual framework for examining the probability of the occurrence of a disaster. However, the concept of 'vulnerability assessment' defines the probable effects of dangers on the life of humans and their belongings within a predefined area [3]. Therefore, seismic vulnerability typically exhibits physical, environmental, and socio-economic aspects [4,5]. This is based on the fact that cities are more vulnerable to disaster as a result of huge populations, building stocks, and infrastructure. Therefore, the status of a seismic vulnerability assessment (SVA) in urban areas is crucial to be assessed [6]. Numerous techniques have been suggested by researchers to perform SVA on an urban scale. However, selected studies have employed prevailing analytical relations or vulnerability indices described in the framework for Spatial Decision Support Systems (SDSS) (e.g., refs. [7–14]). However, the outlined approaches are relevant only for predefined relations or directories explained, particularly for the area under the study. The lack of comprehensive building inventory and/or destruction statistics of past earthquakes can be clearly observable for many highly susceptible urban areas. Furthermore, insufficient attention has been given to the implementation of seismic vulnerability assessment methods in areas with limited data availability [15]. Due to the limitation of data and the necessity to assess structural and environmental seismic vulnerability, an applicable solution is to propose SVA for urban residential buildings [2,16]. In this regard, some researchers have employed methods based on Geospatial Information System such as GIS-based Multi-Criteria Decision Making (MCDM) [16–22]. However, the inherent uncertainties linked to SVA through the MCDM procedures could considerably influence the assessment results. There are limited studies that have considered and addressed the integrated uncertainties. For instance, fuzzy logic was used to evaluate the uncertainties associated with the MCDM procedures, which was approved for the SVA of structures in Los Angeles [2]. Likewise, the human loss maps for the Tehran municipal area (the capital city of Iran) were recorded using sensitivity based fuzzy logic [23]. Other studies have suggested models for SVA in Tehran using the rules of deriving decision based on the technique of granular computing [24]. Similarly, the ordered weighted averaging operator (OWA) was adopted to create a vulnerability map through statistical units for Tehran [25]. In the approaches used to study the seismic vulnerability of Tehran, the vulnerability of each statistical unit has been addressed by experts, individually. In other words, experts rank the selected sample statistical units according to their seismic vulnerability; hence, the defined rules are dependent on individual case study units. Urban earthquake vulnerability assessment of Tabriz city based on the Analytic Network Process and Artificial Neural Network (ANP-ANN) was performed by ref. [26]. The study established a novel hybrid framework for creating a composite vulnerability index based on socio-economic, environmental and physical indices.

Currently, vulnerability assessment and modelling behaviour of buildings related to earthquakes are a major concept in hazards studies [2,8,19,27–35]. These investigations have identified the effective factors in earthquake hazard assessment and applied different methods for producing a seismic hazard map. Identification and reduction of the seismic vulnerability of residential buildings with respect to impending earthquakes are essential. Based on Standard 2800 [36], residential buildings are among the most crucial structures. Upgrading residential buildings against earthquakes is extremely necessary for the reduction of loss of lives and properties. Consequently, in this research, the main factors in the seismic vulnerability of residential buildings in an urban environment were identified. The structural information, geological and geotechnical data have been considered. The weight assigned to the criteria (layers) and the alternatives (classes) of each criterion was calculated based on the analytic hierarchy process (AHP). The geotechnical and structural vulnerability maps have been developed using geographical information system (GIS). Herein, Geographic Information System-based Multi-Criteria Decision Analysis (GIS-based MCDA) provides a collection of powerful techniques and procedures converting spatial and non-spatial data into information within decision maker's own judgment [37]. Finally, the seismic status of residential buildings at the time of earthquake occurrence has been analysed by overlaying these two maps. The main questions that can be considered for this investigation are: (i) can MCDM methods be implemented for SVA in urban areas addressing the shortage of the current knowledge?; (ii) is it possible to propose novel insights into the criteria implemented for SVA?; and (iii) does the MCDM model for SVA of urban residential buildings provide useful information in a real urban environment? Therefore, this research contributes to the SVA of urban residential buildings by (i) revealing the necessity and efficiency of applying MCDM methods for SVA in areas to treat the inadequacy of the existing knowledge; and (ii) proposing an innovative insight into the adopted criteria. Subsequently, seismic risk indicators were considered in two main categories, including the indicators that influence ground motion intensity and the indicators pertinent to structural properties that influence buildings' vulnerability. The proposed method was implemented in Tabriz city (Figure 1), which is a seismic hazard-prone metropolis in the northwest of Iran [12,26,38,39]. The main objective of this research is to identify urban statistical units with higher residential building damage estimates in municipality zones of Tabriz. The most devastating earthquake magnitude that Tabriz has experienced, based on the historical records, is as large as Ms ~ 7.7 (1780 A.D), which was due to the movement of the North Tabriz Fault (NTF) [40]. This was hypothesised as the earthquake scenario of the present study. However, damage caused by secondary disasters such as liquefaction, landslides, fire, and explosions are not included in this study. This research accomplishes that the suggested approach can be a practical model for a quick and efficient SVA in urban areas to handle the incorporated uncertainties.

2. Materials and Methods

2.1. Geological and Seismic Characteristics of the Case Study

The province of East Azerbaijanis is located in NW Iran (Figure 1). It is situated on the Turkish–Iranian plateau where ongoing Arabian–Eurasian convergence is partitioned between thrusts and strike-slip faults in NW Iran and eastern Turkey [41,42]. Tabriz city is the Capital County of East Azerbaijan with a population of approximately 1,600,000. The North Tabriz Fault (NTF) is a right-lateral strike-slip fault, in which houses converged on sections, thereby forming the northern border of the Tabriz basin (TB) expressed as a clear surface topography [43]. It is the south-eastern continuation of the Gailatu-Siah Chesmeh-Khoy and Chalderan (Chaldiran in Turkish) faults that ruptured in 1976 with an Mw 7.1 earthquake in Turkey near the Iranian border [44]. Though intermittent, the right lateral system of strike-slip faults seems like the south-eastern continuation of the North Anatolian Fault which extends into NW Iran [42,45]. The listed faults are due to shattering historical earthquakes in Tabriz in 858, 1042, 1721, 1780, and 1965 AD [40]. The historical earthquakes caused tens of thousands of casualties and extensive physical and social destruction in the city. A recent time series analysis of RADAR images in the area between 2004 and 2010 supports a probable earthquake of M ~7 as a result of strain accumulation across the NTF [46]. Historically, the earthquakes resulted in widespread socio-economic, physical devastation and loss of thousands of human lives in the city. A current time series examination of RADAR imagery of the area from 2004 to 2010 indicates a plausible earthquake of M ~ 7 due to strain accumulation through the NTF [43]. There is a lack of useful data for evaluating the seismic vulnerability of Tabriz. For instance, there is a shortage of data on the area-specific fragility curves or pre-defined seismic vulnerability codes/indices for current structures. Therefore, it is critical to recommend a practical and rapid assessment model for seismic vulnerability assessment to enable local policymakers during mitigation and preparation activities.

Historical records and instrumental archives prove that NW Iran and Eastern Turkey were struck by many destructive earthquakes [47]. The most recent and the largest earthquake is Mw 7.1, on 23 October 2011, the Van earthquake, which was linked to the reverse slip on the NE-SW trending fault [48]. Seismologists believe that another strong earthquake will probably occur in Tabriz city. Furthermore, historical studies have revealed that Tabriz was shattered by numerous destructive earthquakes necessitating the development of frameworks for local and national assessment on an urban scale. However, there are no sufficiently detailed or descriptive records of these events to permit an accurate assessment of the ground devastation and deformations [49,50].

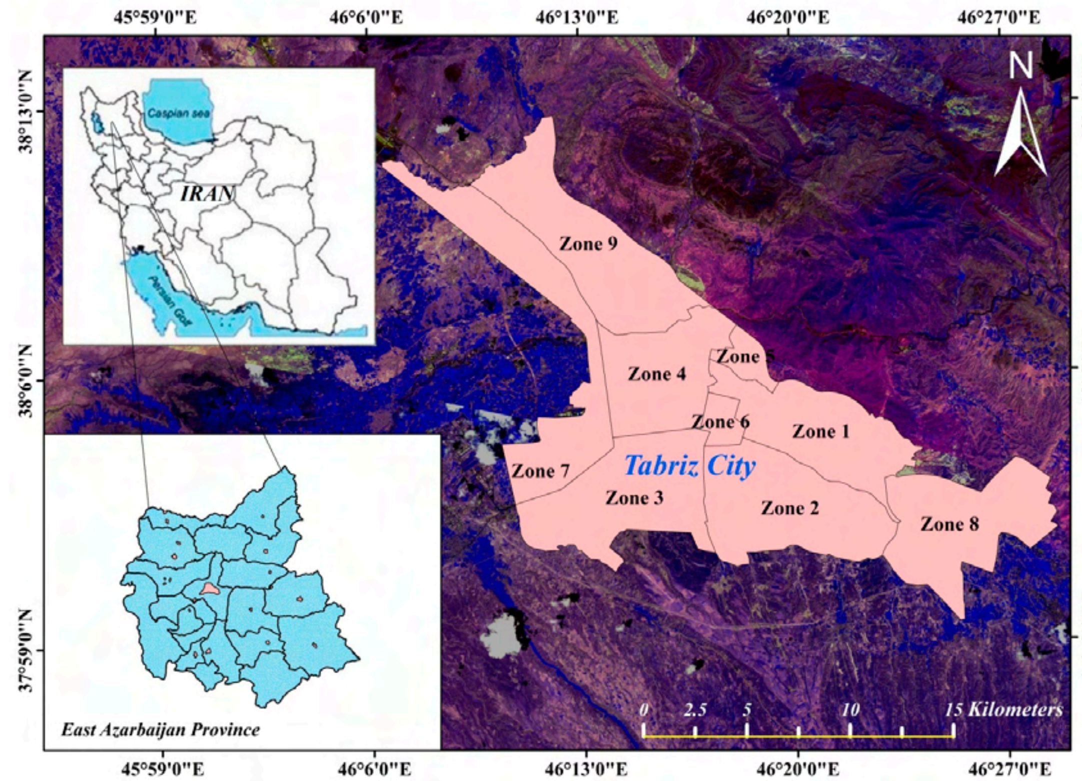

Figure 1. Geographical location of the East Azarbaijan province and Tabriz city in relation to the political provincial and national border.

2.2. Analytic Hierarchy Process (AHP) Model

Typically, decision-makers are required to adopt definite criteria to make a decision. If the criteria are quantitative, then somewhat similar mathematical methods are required to address them. Conversely, since the decision-making criteria can be either quantitative or qualitative conflicts can arise. However, this can be addressed using needs-specific methods like multi-criteria decision making (MCDM) procedures. Therefore, the MCDM comprises a series of methods (e.g., correlation analysis or weighted sum) that permits specialists to consider and allocate marks or to classify the collection of criteria linked to the specific issue [51,52]. Therefore, the combination of MCDM and GIS-based methods presents an exclusive capacity to manage and analyze spatial data resulting in various spatial decisions. The most commonly applied method of the MCDM reported in the literature is the analytic hierarchy process (AHP) [53]. This procedure applies the three principles of decomposition, comparative judgment and prioritized synthesis. During the decomposition stage, the decision-making problems are disintegrated into the hierarchy form based on the various elements. Generally, the first stage involves developing a criteria and sub-criteria tree structure. The comparative judgment principle comprises of a couple of wise assessments of accessible alternatives at the hierarchical level. Hence, the level elements are matched with other elements of a similar level so that the relative importance of each is computed as presented in Table 1.

Table 1. Fundamental scale for pairwise comparisons in the AHP [54].

Weight/Rank	Intensities
1	equal
3	moderately dominant
5	strongly dominant
7	very strongly dominant
9	extremely dominant
2, 4, 6, 8	intermediate values
Reciprocals	for inverse judgments

Application of the AHP method in spatial decision making involves the following steps.

- *Calculating the criteria scores*. Each alternative is compared pairwise with respect to a specific criterion to obtain the scores ($x1, \ldots xn$) of alternatives. The eigenvectors are obtained after normalising the judgmental matrices.
- *Calculating the criteria weights*. Saaty (2008) [54] used the lambda max technique to obtain criteria weights by applying the pair-wise comparison method. Alternatives are compared pairwise with respect to each criterion to obtain weights ($wi \ldots wn$). Every matrix has a set of eigenvalues and for every eigenvalue, there is a corresponding eigenvector. In Saaty's lambda max technique, a vector of weights is defined as the normalised eigenvector corresponding to the largest eigenvalue λmax.
- *Local priorities and consistency of comparisons.* Once the judgmental matrix of comparisons of criteria with respect to the goal has been evaluated, the local priorities of criteria are obtained and the consistency of the judgments is determined. The scale of the pairwise comparison was introduced by Saaty (Table 1). It has been generally agreed that priorities of criteria can be estimated by finding the principal eigenvector w of the matrix A. That is:

$$AW = \lambda \text{max}^{\omega} \quad (1)$$

When the vector is normalized, it becomes the vector of priorities of the criteria with respect to the goal. λmax is the largest eigenvalue of the matrix A and the corresponding eigenvector w contains only positive entries. The consistency of the judgmental matrix can be determined by a measure called the consistency ratio CR defined as:

$$CR = \frac{CI}{RI} \quad (2)$$

where RI is the random index and CI is the consistency index which provides a measure of departure from consistency. The consistency index is calculated as:

$$CI = \frac{(\lambda \text{ max} - n)}{n - 1} \quad (3)$$

where λmax is the largest eigenvalue of the matrix A and n is the number of criteria. RI is the consistency index of a randomly generated reciprocal matrix from the 9-point scale, with reciprocals forced. Saaty (1980, 2000) [53,55], has provided average consistencies (RI values) of randomly generated matrices (up to size 11_11) for a sample size of 500. The RI values for matrices of different sizes are shown in Table 2 [56]. If the CR of the matrix is higher, it means that the input judgments are not consistent, and hence are not reliable. In general, a consistency ratio of 0.10 or less is considered acceptable. If the value is higher, the judgments may not be reliable and needs to be elicited again.

Table 2. The average consistencies of random matrices (The Random Index—RI-values).

Size	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The weight results computed are considered satisfactory as long as reasonable values of the consistency ratio are obtained. In this paper, the analytic hierarchy technique was adapted to collectively assess the spatial information required to devise a map of seismic vulnerability for Tabriz city and the residential buildings therein. Apropos of the above, the methods approved in the study are defined as such. Lastly, the schematic for the seismic vulnerability map in the research study area is presented in Figure 2 based on AHP and GIS techniques.

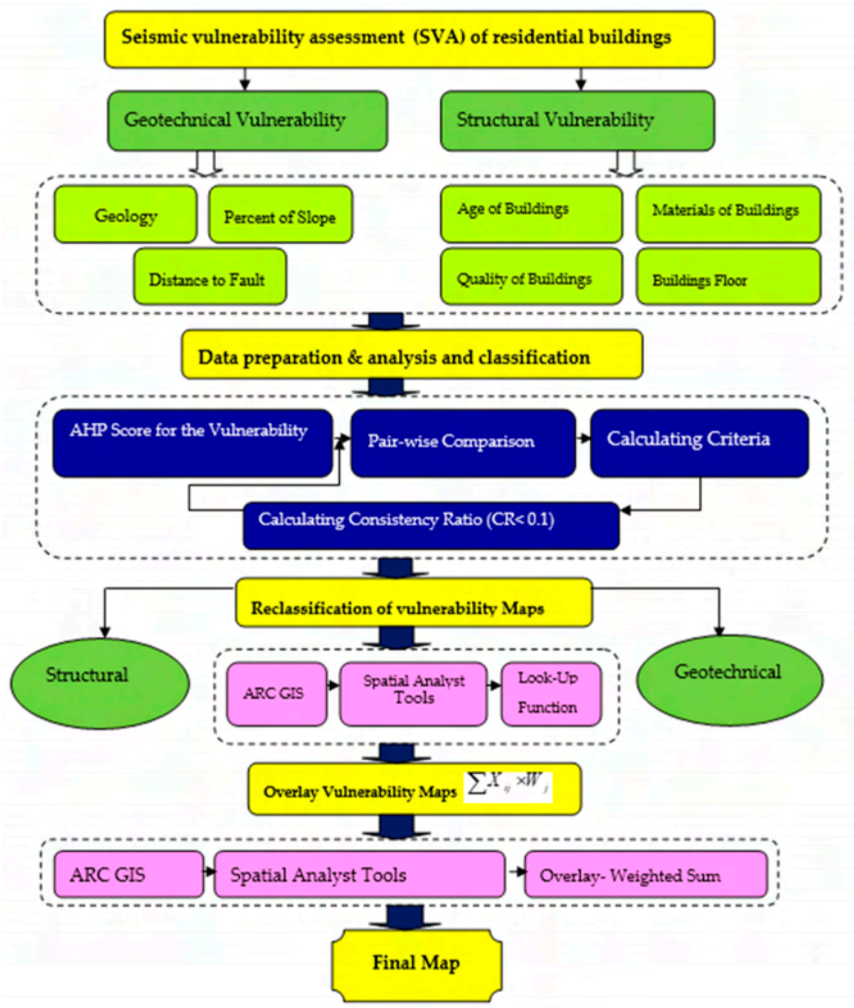

Figure 2. Flowchart of the methodology illustrating the various stages of the analysis for the preparation of the seismic vulnerability map of the study area.

The model equation proposed by ref. [57] was used to compute the over-all values in the study. Therefore, the individual weighted output pixels in the vulnerability maps (*Wi*) was computed based on the following relation:

$$Wi = \sum_{j} xijwj, \tag{4}$$

The terms *xij* represent the valued rank of the *i*th class based on the *j* th layer, and *wj* is the normalized weight of the *j*th layer. The absolute weight can be acquired by increasing the normalized weighted rate of every layer in the consistent rank and sum of the layers in the class.

1. Lastly, as the process of defining the vulnerability of residential buildings is along of all the geotechnical and structural factors of an earthquake, they should be measured simultaneously. Therefore, the seismic vulnerability of the residential buildings in Tabriz city was computed by superimposing the two acquired maps.

2.3. Kernel Density Estimation (KDE)

Kernel density estimation (KDE) is a non-parametric way to estimate the probability density function of a random variable. Kernel density estimation is a fundamental data smoothing problem where inferences about the population are made, based on a finite data sample [58,59]. Let $(x_1, x_2, \ldots, x_n)$ be a univariate independent and identically distributed sample drawn from some distribution with an unknown density f. We are interested in estimating the shape of this function f. Its *kernel density estimator* is

$$\hat{f}_h(x) = \frac{1}{n}\sum_{i=1}^{n} k_h(x - x_i) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{x - x_i}{h}\right) \tag{5}$$

where K is the kernel—a non-negative function—and $h > 0$ is a smoothing parameter called the *bandwidth*. A kernel with subscript h is called the *scaled kernel* and defined as $K_h(x) = 1/h\ K(x/h)$. Intuitively one wants to choose h as small as the data will allow; however, there is always a trade-off between the bias of the estimator and its variance. The KDE model was used to obtain the density of the layers of the buildings quality, buildings materials, the size of buildings blocks and buildings floors density in this study.

2.4. Data Preparation and Analysis

Vulnerability maps are unable to be produced without taking into account the separate criteria and indicators causing the heterogeneity of the study area. Actually, this is the most vital part of the overall approach that ensures the selected criteria and the indicators are adequate to reflect the overall vulnerability of urban areas in Tabriz city. Selecting indicators is an extremely time-consuming part of the method because it consists of the construction and preparation of a GIS spatial database that will later be used during earthquake vulnerability analysis and served as input to urban earthquake scenarios. There are several criteria and indicators employed for an urban vulnerability assessment (See Table 3). Classification is not straightforward as there are no statistical rules which can classify continuous data automatically [60]. Many researchers use their own discretion on the matter of dividing the class boundaries from continuous data, as it is vague. Mathematical methods for data classification based on equal intervals, manual or natural breaks, or statistical consideration are default processes in GIS software [61]. The manual classifier method has been applied to classify the values into five different vulnerability classes. To calculate density, kernel density function was used. To calculate distance, a Euclidean function with a cell size of 10 m (pixel size 10 × 10 m) was applied in the Arc GIS environment (version 10.3). Thereafter, reclassification of layers has been applied after the classification process to make standard value between 1 and 5. One of the novelties in this research is to use Kernel density estimation (KDE) model to obtain the density of the layers of the buildings quality, buildings' materials, the size of buildings blocks and buildings floors density. Obviously, standardization of criteria is one of the important issues for decision-making models. There are many standardization methods; the classification method is one of the simplest and most widely used. For this, the layers were divided into 5 classes (2 classes of suitable conditions, 2 classes in unsuitable domains and one medium class). The 1 to 5 scaling code was applied for quality layers, including the quality of the building and buildings materials based on the value and strength of the structure. For layers of the size of buildings blocks and floors, these layers were also coded again 1 to 5 during the classification. These changes are made in the layer's database (Attribute Table). Then, the layers (as polygonal) were converted into point and eventually run in the KDE model in the Arc GIS software environment. In the next step, we reclassified the geotechnical and structural layer in ARC GIS environment using spatial analysis, and the look up function added the final weights to each layer. Subsequently, final geotechnical and structural weights (weighted sum) in spatial analyst function and final residential building vulnerability map were overlaid. The proposed model requires a number of stages, which are shown in Figure 2.

Table 3. The acquired data and the stakeholder organizations.

Papered Data	Abbreviation	Scale	Source
Distance to fault	DF	1.100000	1
Percent of Slope	PS	1.2000	6
Geology	PG	1.100000	2
Buildings Materials Density	BMD	1.2500	4
Size of Building block Density	SBDD	1.2500	4
Quality of Buildings Density	QBD	1.2500	5
Buildings Floors Density	BFD	1.2500	4

1. Consulting engineering of Tehran Padil. http://www.tehranpadir.com. 2. Iranian Geological organization. http://www.gsi.ir/. 3. Census Center of IRAN. http://www.amar.org.ir/. 4. Department of road and Urbanity (East Azerbaijan Province). http://ea-mrud.ir/. 5. The municipality of Tabriz City. http://www.tabriz.ir. 6. DEM 30-m Aster. http://earthexplorer.usgs.gov.

2.4.1. Geotechnical Vulnerability Factors

For the regions with seismic activity, evaluating the geotechnical seismic vulnerability is vital for urban expansion and development. As a result, to ignore or not classifying areas with a significant risk of earthquakes enhances the probability of seismic vulnerability and destruction. In general, seismic hazards are typically estimated by examining previous earthquake activity in the area. Consequently, the confirmation related to the probability of the structure tolerates disturbances inside the fault zones and the mode of travel of the seismic waves above the crust and overlying soil beneath the sites. It is important to reiterate that during an earthquake, the incidence of surface separation, soil liquefaction, and landslides, accompanied by peak ground acceleration (PGA), constitute the secondary events rising from the ground movement, which intensify the seismic vulnerability and devastation. Therefore, they must be considered when estimating the overall seismic vulnerability. However, the occurrence of these actions is linked to the subsurface plane above a major release and after effects such as movement and folding such as lateral spreading. Due to inadequate data on layered sub-surfaces and surface rupture, landslides and soil liquefaction in Tabriz city were not analysed in this study.

Distance to Fault

Among the major procedures employed for preventing the devastating impact of earthquakes is to avoid the area with high risks. Therefore, the choice of location is an essential stage in planning buildings or settlements located in seismic susceptible zones. The importance of site location is a vital approach to risk assessment and hence high-risk areas should be avoided. This factor (Distance to a fault) has the highest importance and rate among the applied models in the evaluation of vulnerability. Typically, the vulnerability factor decreases by increasing the distance from the fault lines and vice-versa. According to Figure 3a, with the exception of zone 3 and industrial sites located southwest part of the city, other zones are not ideal because of their locations nearby the faults. Generally, this is because the fault line passes through the other zones except for zones 2 and 3 in Tabriz municipality. Therefore, land use in these areas particularly for residential and commercial uses is unsuitable. However, the solution to the underlying problem requires a comprehensive review of Tabriz's situation particularly due to its vulnerability to earthquakes. In addition, the settlement of large parts of the city on fault lines shows the deteriorating condition of the outlined areas.

Slope

The slope is one of the most important environmental factors that is vulnerable to earthquakes. One of the necessary conditions for earthquakes is high gradients. As a basic parameter, the slope is for environmental attributes' derivation and affects many important landscape processes such as erosion potential, runoff rates and velocity of overland and subsurface flow. The slope is an important sub-criterion in the proposed methodology which was expressed in percent [62]. The occurrence of earthquakes is typically higher in seismic-prone areas with high gradients due to constructions and structural densities on surfaces. In this case, avoiding construction on these surfaces is important. According to the location of the city, Tabriz is idyllically located on lands with gradients below 5%, as depicted in Figure 3b. Therefore, large parts the northern of the city comprise marginal regions with highly dense population located on lands of gradients above 5%. Likewise, the southern areas do not demonstrate complimentary conditions based on a gradient. Nonetheless, improved conditions occur at comparatively large distances from fault lines, where the population and structural density are low.

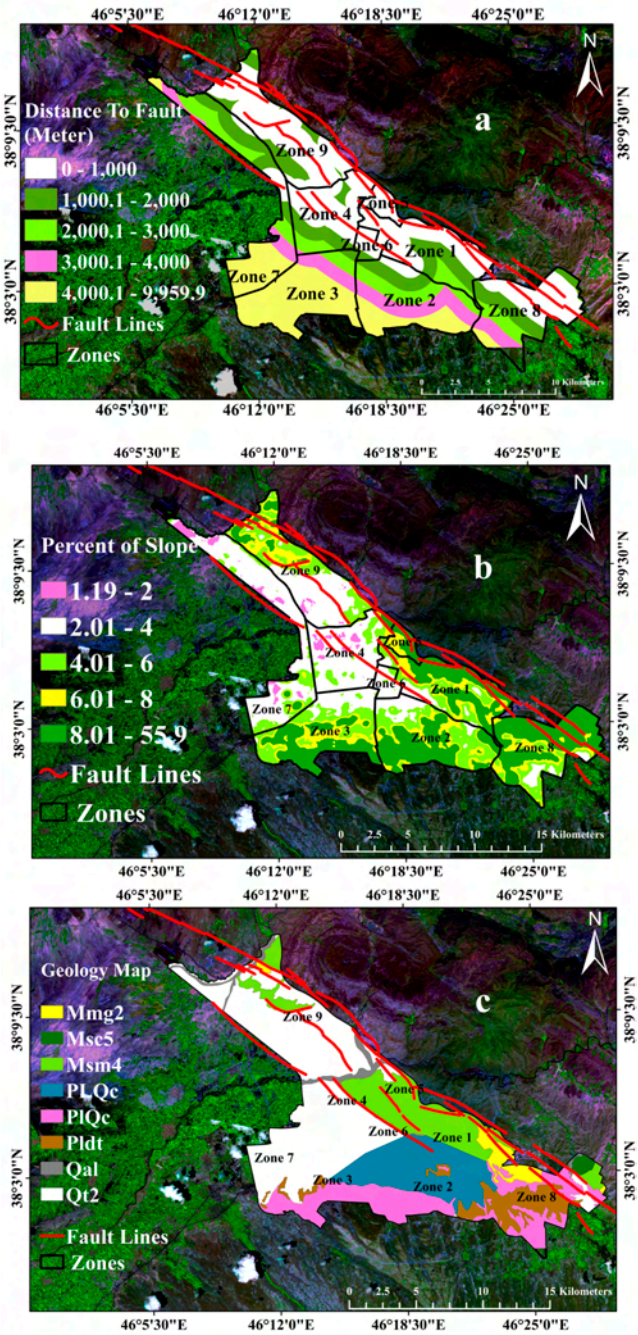

Figure 3. Distribution of (**a**) Fault systems (**b**) Slope gradients and (**c**) Geology map of Tabriz city. Mmg2 = Interlayer of greenish grey marl associated with an interlayer of gypsum- bring sandy marl. Msc5 = Interbedded red conglomerate with sandstone and red marl. Msm4 = Sandstone and red marl. Pldt = Diatomic and fish interbedded with fine particles sediment. Plqc = Interlayer of semi-hard conglomerate associated with sandstone and pumice. Plqc = Interlayer of semi-hard conglomerate associated with sandstone and pumice. Qal = Quaternary alluvium. Qt2 = Young terrace and alluvium deposits.

Geology

The sustainable use of underwater resources in urban areas requires an in-depth understanding of geological and hydrological processes. Furthermore, this comprises the short and long-term impact of human activities on underwater resources [63]. In addition, the identification of the body of land is significantly important in urban and regional planning. These form factors include the soil type, gradient, and texture. Other factors include the type and composition of the rocks as well as water permeability along with the manifestation of fractures and faults located on the land. The outlined forms directly influence the geological structure and rock-forming elements considered vital for urban design and planning. The city of Tabriz is geographically comprised of the resulting units such as red marl, ridge sandstones and early alluvial barracks. The red marls include an interchange of green, grey, and red with the internal layers comprised of sandy, gypseous, and saltine marls. Conversely, the contemporary alluvial includes residues of clastic granules and sediments of diatom fish. Additionally, the sandstones layers, pyroclastic rocks, basic and ultra-basic rocks make up the semi-rigid conglomerate. This also involves puns and red conglomerate with an interchange of sandstone and red marl. Figure 3c shows the geology map of Tabriz city.

2.4.2. Factors Influencing Structural Vulnerability

The historic and geographic scope of Tabriz city along with the diversity of its citizen's livelihoods means that the city is structurally diverse. In general, the structures in Tabriz city comprise of Qajar era buildings which are around 100 years old, merged with villages with other buildings that date back 20 to 50 years, along with new constructions and towers. Consequently, the structural vulnerability of a city with such varied distribution and native structures requires the experiences of past earthquakes, based on the prepared Standard 2800 [36], and studies in the literature [29,32,33,35,64–68]. After extracting significant factors like materials, age, quality of construction, along with the seismic resonance, structural coefficients, and scoring the parameters, the map of structural vulnerability was generated for Tabriz city (Figure 4a–d). It is noteworthy to state that this aspect of the research employed additional categorizations according to Standard 2800. This is a collection of guidelines established at the Building and Housing Research Centre of Iran from past experiences with earthquakes. This is the single most official and scientific material for the design and evaluation method for seismic-resistant structures and determining the seismic vulnerability of earthquake-prone structures. As outlined in the guidelines, the key to the seismic stability of structures is based on the building materials, the size of building blocks, quality of the buildings, and building floors.

Buildings Materials

There are diverse categories of materials used in the construction of the building. Among the most essential is the ranking of earthquake-proof structures described in Standard 2800 [36]. Based on the regulation, four categories of structures can be distinguished based on the construction materials. Typically, these can include; steel, concrete or masonry buildings (brick and cement block or stone), sun-dried mud bricks and building made from wood. The empirical findings of experts obtained from laboratory experiments and previous earthquakes observations show that the most vulnerable structures are those erected with solar-dried mud bricks. These are known to completely collapse the magnitude of the earthquake exceeds 6, although the decrease in vulnerability was observed for buildings erected with masonry, concrete, and steel as reported in the literature, [50,65,69,70]. (see Figure 4a). Hence, wooden skeleton structures have higher strength than non-strengthened mortar walls. However, some structures can remain undamaged even after severe earthquakes. For this study, coding the buildings was done based on types of the materials as presented in Table 4.

Table 4. Rating type of building's materials.

Classification's Type of Materials	Quality Code
Cemented block, iron, stone, the composition of brick and weak materials	1
Brick and iron	2
Reinforced concrete and other composite materials	3
Under construction	4
Metal skeleton	5

Size of Buildings Blocks

The evaluation and segmentation require comprehensive assessment and knowledge of the geometry of land and its properties. The specification of buildings directly impacts the structural performance, construction characteristics, and network of roads vital to the evaluation of the vulnerability index. In the evaluation of vulnerability to earthquakes, the shape and geometric size of the land structure are vital (see Figure 4b). In practice, the plots of land characterized by large yet consistent shapes or sizes are less vulnerable. The lower limit of segmented land is typically 200 m^2 although this threshold is not constant and may vary according to the local economy or environmental conditions. The segmentation of blocks in this study is presented in Table 5.

Table 5. Rating the segmentation of buildings.

Classification of the Segmentation of Buildings (m^2)	Rating
0–200 square meters	1
200.1–300 square meters	2
300.1–400 square meters	3
400.1–500 square meters	4
500.1 square meters and higher	5

Buildings Quality

The design of a building or structure includes the collaboration of different groups, each responsible for different sections. As a result, the structural quality is reliant on various factors, including the employer's level of education and income. Other pertinent factors include the structural design standards, quality of manufactured materials, and the insurance of the structure [25]. The quality of newly constructed, repaired or destroyed buildings is a major indicator of vulnerability assessment. The quality of buildings and its properties such as resistance against earthquakes can be measured on a scale of 1–5 with the highest score being 5 as presented in Table 6. After rating the quality of buildings as an attribute table (Table 6), the required density was determined using the Kernel Density Estimation (KDE) in ARC-GIS environment. The Kernel Density function was functioned based on three factors (i) distance (bandwidth or band radius of analysis), (ii) a number of phenomena, and (iii) their rates (See Figure 4c).

Table 6. Rating the quality of buildings.

Classification of Building's Quality	Quality Code
Destroyed	1
Repaired	2
Moderately repaired	3
Especial and under construction	4
Newly constructed and suitable	5

Buildings Floors

The vulnerability of buildings increases with an increase in the height and number of floors. Hence, it is important to note that, despite the numerous innovations in building technologies, greater altitude has failed to lower vulnerability. Nonetheless, the number of floors in buildings remains an important dynamic in measuring seismic vulnerability. The pattern obtained from the Kernel Density Estimation (KDE) function clearly displays the density of buildings based on the number of residential units and floors within the 320 m radius (see Figure 4d). Therefore, increasing the number of floors in high-risk areas must be strictly prohibited through enforcement of statutory regulations and strict supervision by relevant authorities.

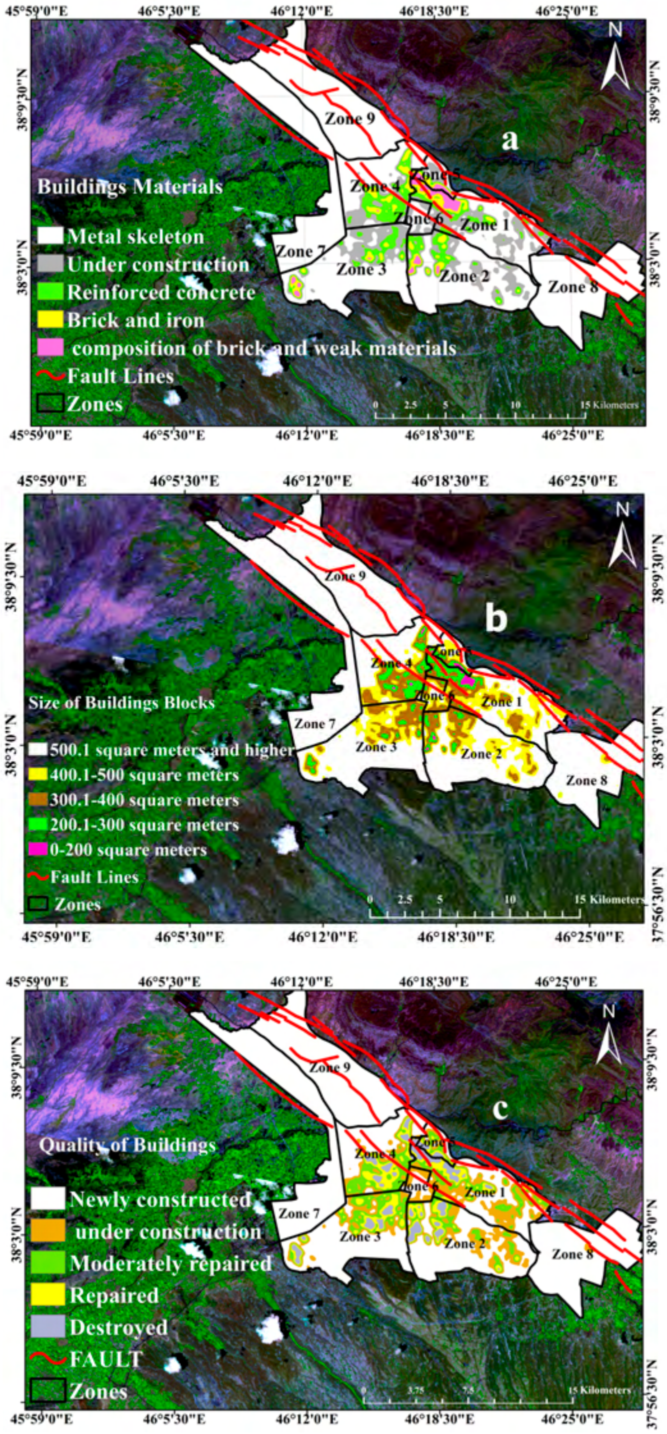

Figure 4. *Cont.*

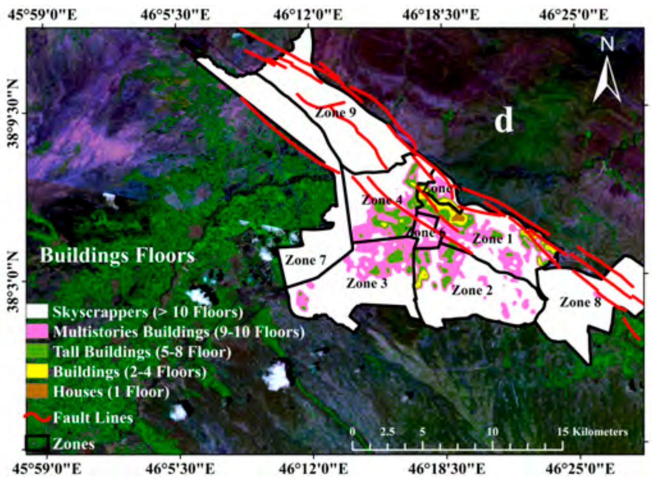

Figure 4. Distribution of (**a**) buildings materials (**b**) size of buildings density (**c**) quality of buildings and (**d**) buildings floor in Tabriz city.

3. Results

Using AHP and determining the importance of each used sub-factors and indicator in the study, with respect to two main factors (Tables 7 and 8), the results are as follows.

Table 7. Pairwise comparison matrix, sub-factors weights of the data layers.

Geotechnical Sub-Factor Factors	**Distance to Fault**		**Geology**	**Percent of Slope**
Distance to Fault	1		3	3
Geology	1/3		1	5
Percent of Slope	1/3		1/5	1
∑	**1.66**		**4.2**	**9**
Structural sub-Factors	Buildings Materials	Quality of Buildings	Size of Buildings Blocks	Buildings Floors
Buildings Materials	1	3	5	7
Quality of Buildings	1/3	1	3	3
Size of Buildings Block	1/5	1/3	1	3
Buildings Floors	1/7	1/3	1/3	1
∑	**1.67**	**4.66**	**9.33**	**14**
Main Factors	Geotechnical		Structural	
Geotechnical	1		2	
Structural	1/2		1	
Σ	**1.50**		**3**	

Table 8. List of the dataset and computed weights and Consistency ratio of the data layers.

Geotechnical Sub-Factors	**Distance to Fault**		**Geology**	**Percent of Slope**	**Weights**
Distance to Fault	0.60		0.56	0.55	0.59
Geology	0.30		0.36	0.40	0.35
Percent of Slope	0.1		0.08	0.05	0.07
Consistency ratio: 0.05					
Structural Sub-Factors	Buildings Materials	Quality of Buildings	Size of Buildings Blocks	Buildings Floors	Weights
Buildings Materials	0.56	0.52	0.52	0.51	0.51
Quality of Buildings	0.28	0.26	0.23	0.27	0.26
Size of Buildings Block	0.07	0.10	0.10	0.14	0.10
Buildings Floors	0.09	0.12	0.09	0.08	0.09
Consistency ratio: 0.09					
Main Factors	Geotechnical		Structural	Weights	
Geotechnical	0.70		0.63	0.66	
Structural	0.30		0.38	0.34	
Consistency ratio: 0.01					

Generating Geotechnical, Structural and Overlay Maps

The first map acquired through processing the geotechnical susceptibility of residential buildings in Tabriz city is based on five categories, namely very high, high, medium, low and very low (Figure 5). The results showed that 20.11% of the entire area was extremely vulnerable. High, moderate, low and very low vulnerable zones represent 12.91%, 29.31%, 23.35% and 14.33% of the area, respectively (Table 9). Based on the geographic position, the southeast areas of the city comprising zones 2, 3 and 7 represent the regions with low or very low vulnerability. Despite the high slopes in the zones 1, 2, 3, 8, and 5, because of the minimum amplitude of peak ground acceleration and the low probability of liquefaction occurrence. However, in the south to northern regions, namely zones 1, 4, 5, 6, 8 and 9 are considered highly vulnerable areas because of the North Tabriz Fault (NTF), high slope and liquefaction occurrence (see Figure 5).

Table 9. The level of residential buildings vulnerability in Tabriz city according to their geotechnical vulnerability.

Vulnerability	Percent
Very High	20.1
High	12.9
Moderate	29.3
Low	23.4
Very Low	14.3
SUM	100

Based on the structural vulnerability map, Tabriz city is broadly classified into five zones; very high, high, medium, low and very low, as shown in Figure 6. From a numerical perspective, 2.38% of residential buildings have very high, 3.90% high, 4.93% medium, 13.47% low structural vulnerability, and 75.32% are classified as very low buildings (Table 10). However, geographical distribution indicates that zones 5, 4, 3, and 2 are the most vulnerable buildings, whereas the low and very low buildings are located in zones 9, 7 and 8 (see Figure 6). Earlier exploration of the area's history shows the cause of the vulnerability or of the low and very low condition of existing buildings. Selected buildings in zones 4 and 6, which are considered as the central part of Tabriz city, were built during the era of Qajar in 1924, which means most remain untouched because of being cultural heritage.

Zone 5 and the north of zone 1 are considered the first and oldest settlements for immigrants. Hence, the structures typically fail to adapt to the prerequisite criteria. This primarily ascribed to lack of funding, cultural weakness, and low awareness of their residents. Furthermore, a few buildings are constructed without the approval of the relevant authorities or designated organizations. In addition, the expansion of the municipal borders in zones 1, 4 and 5 containing large informal settlements has exacerbated the vulnerability of buildings in these areas. For that reason, a specific strategy is essential to renovate buildings in the aforementioned zones in Tabriz city since the magnitude of high-quality steel and concrete buildings is quite small. Principally, the largest number of steel and concrete buildings can be found in zone 5, with most characterized by the low quality of construction that fails to meet the standard requirements. Consequently, strict compliance with the necessary construction standards or requirements for new buildings is necessary. However, the observance of principles of buildings construction, as well as inaccuracy of newly constructed buildings in southern parts of zones 1 and 2 by the municipal government, has resulted in low and very low vulnerable buildings in these parts.

As the foremost aim of the current study is to describe the seismic based vulnerability of the residential structures in Tabriz, it is important to overlay the final geotechnical and structural maps as depicted in Figure 7. The results show that major residential buildings situated in zones 1 and 5 along buildings in zones 2, 6 and 3 exhibits high seismic vulnerability. However, a few residential buildings located in zones 9, 7, 8 and other buildings in these zones are considered very safe in Tabriz city (see Figure 7).

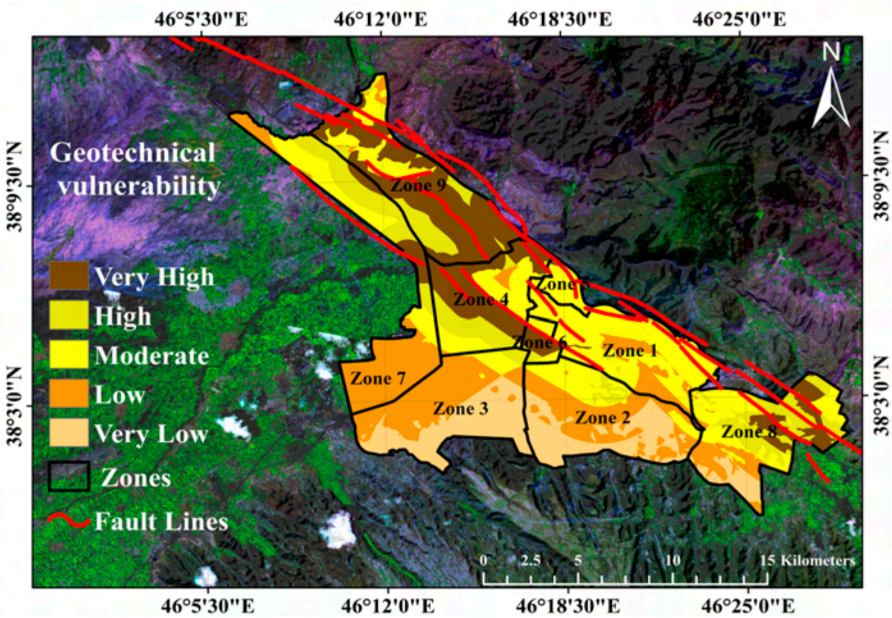

Figure 5. Residential buildings vulnerability distribution showing geotechnical vulnerability in Tabriz municipality.

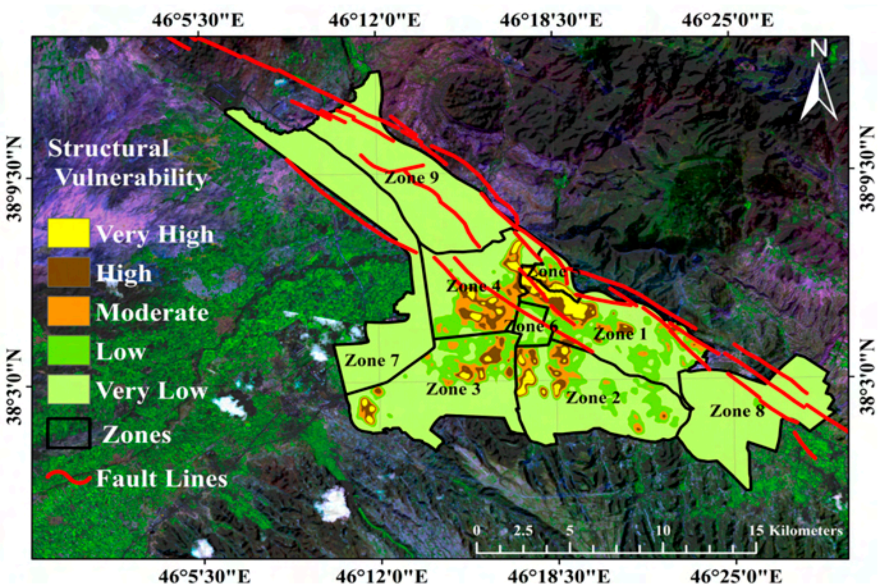

Figure 6. Residential buildings vulnerability distribution showing structural vulnerability in Tabriz municipality.

Table 10. The level of residential buildings vulnerability in Tabriz city according to their structural vulnerability.

Vulnerability	Percent
Very High	2.38
High	3.9
Moderate	4.93
Low	13.47
Very Low	75.32
SUM	100

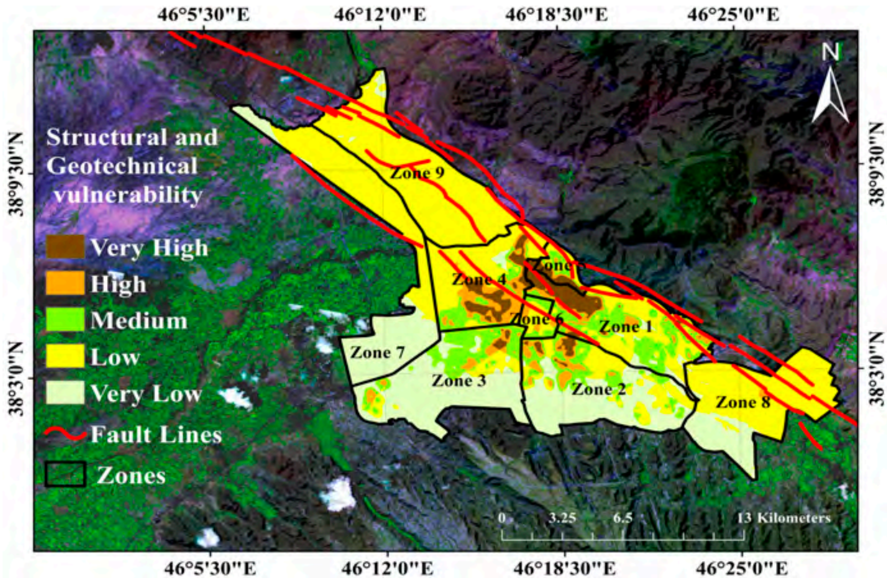

Figure 7. Residential buildings vulnerability distribution showing structural and geotechnical vulnerability in Tabriz municipality.

4. Discussion

The vulnerability is multi-dimensional, differential and varies across physical space and within social groups. In addition, it is scale-dependent with regards to space and units of analysis such as individual, household, region, or system with dynamic characteristics and driving forces of vulnerability change over time. Vulnerability assessment is a broad concept that can be discussed in several different contexts. However, it is not a variable that can be measured directly but can be assessed indirectly according to a set of dimensions. For assessing urban vulnerability, it is necessary to consider all main dimensions of vulnerability including environmental, physical and socio-economic [71,72]. Physical factors are usually materially oriented arising from the field of engineering, architecture and land use planning. Vulnerability from a physical perspective, despite its broad scope, refers mainly to the consideration and susceptibilities of location and building environment. Environmental vulnerability includes the fraction of the slope, geological features and distance to the fault. The identification of vulnerability and understanding of related methodologies helps the development of policies and action plans for mitigation. Hence, the results can enhance urban policy and scientific based debates as a possible key-element for urban public policies. The main advantage of the research was simplicity in applying the indices, which could be a solution for different stakeholders in vulnerability studies. Thus, vulnerability assessment fits into the general approach of informed decision making which links academic research, policy and practice [73]. Tabriz is located among one of the main seismic (NTF) faults with the high potential of earthquake occurrence. Its residential areas are highly vulnerable to earthquakes due to a dense population, too many structures and violations of construction codes. Thus, in the case of an earthquake, 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; construction of vital structures such as hospitals and schools. In highly vulnerable areas, limitation and establishment of vital roads can be banned or subject to observing all earthquake engineering principles, seismic regulations and construction codes. Risk mapping is often referred to as an essential tool for reducing the risks of natural and technological hazards [74]. Some investigations have used GIS-based MCDM approaches for SVA of urban residential buildings [16–22]. While the inherent reservations linked to SVA using the MCDM procedures could considerably affect the concluded results. For that reason, few studies have considered and addressed the integrated uncertainties [23–25]. In this study, the vulnerability of residential buildings in Tabriz city (as a case study) was investigated based on geotechnical and structural factors and the selected sub-criteria determined from combined GIS and AHP techniques. This research proposes a new rational approach independent of the study area, using a robust MCDM method, which attempts to treat the incorporated epistemic uncertainties [74]. To achieve this target, three approaches of MCDM were implemented in GIS environment [56]. A new insight on the influencing criteria was introduced in this research, which concerns the influencing criteria in two main categories: (i) structural indicator that considers the building structural properties, and (ii) the criteria that influence ground motion intensity, which takes into account the properties of the ground on which the building is constructed. The datasets pertinent to each category are introduced and implemented in a real case study, which was an earthquake-prone municipality district with high seismic risk. The results of this study suggest that the proposed method is arguably a pragmatic and quick approach to solve the complex problem of SVA under the vagueness uncertainty of the criteria influences physical seismic vulnerability. The results of the implementation also indicated that the proposed model has acceptable robustness concerning the weights of the criteria defined using the AHP method. Since all geotechnical and structural criteria, do not have equal importance and value, the vulnerability of buildings is not effective by inspecting elements individually. Therefore, the correct results can be achieved by addressing all elements concurrently. Next, the geotechnical and structural maps have been overlaid to determine the seismic vulnerability of residential buildings (see Figure 7).

Meanwhile, a better understanding of the issue can be achieved by considering five main situations:

1. Buildings with very high geotechnical and structural vulnerability comprise 4.44% of buildings. The most vulnerable structures are situated in zones 5, 4 and 1, and require either demolition or reconstruction.
2. Buildings with high geotechnical and structural vulnerability make up about 5.49% of the buildings in the city of Tabriz. These buildings are mostly located in zones 2, 4, 5 and 6, and their seismic vulnerability can be reduced by the process of retrofitting.
3. Residential buildings which have moderate vulnerability from a geotechnical and structural vulnerability consists of nearly 12.28% of residential buildings in Tabriz city. Most of them are located in zones 6, 8 and 2 and a few in zones 1 and 3. Based on the age of construction, the process of retrofitting or occasionally destruction or renovation of the buildings can reduce vulnerability.
4. Residential buildings which have low vulnerability from equally a geotechnical and structural approach constitute nearly 49.37% of all buildings. The buildings are situated in zones 9, 3, 1 and 6, which are the safest groups of residential buildings in Tabriz city.
5. Residential buildings with very low vulnerability constitute 28.42% of the buildings. Therefore, taking into account the structural and geotechnical circumstances collectively, the buildings are considerably less vulnerable compared to the buildings outlined in classes 1 to 4 (Table 11).

Table 11. The level of residential buildings vulnerability in Tabriz city according to both structural and geotechnical vulnerability.

Vulnerability	Percent
Very High	4.44
High	5.49
Moderate	12.28
Low	49.37
Very Low	28.42
SUM	100

Table 12 presents the comparison of the vulnerable zones in Tabriz city according to the data provided by AHP and Residential Building Vulnerability (RBV). The zones of Tabriz city with the highest vulnerabilities are grouped in zones 5, 4 and 1. Generally, the highly vulnerable area are located in three particular zones due to their geographic positions which are situated at the North Tabriz Fault (NTF). By coinciding the AHP and Residential Buildings Vulnerability (RBV) the lowest vulnerability zones include zones 3, 7 and 9.

Table 12. Level of Residential Building Vulnerability (RBV) according to the proposed model.

Vulnerability	Very High	High	Moderate	Low	Very Low	Percent
Zone1	12.50	16.40	32.00	37.10	2.00	100.00
Zone 2	0.68	29.45	38.71	27.99	3.17	100.00
Zone3	0.00	10.81	5.44	31.67	52.08	100.00
Zone4	3.19	52.68	31.80	11.51	0.82	100.00
Zone5	33.50	25.53	26.76	14.20	0.01	100.00
Zone6	0.00	16.11	53.42	28.85	1.62	100.00
Zone7	0.00	0.00	4.00	4.00	92.00	100.00
Zone8	0.00	0.00	54.00	45.00	1.00	100.00
Zone9	0.00	0.00	20.80	79.20	0.00	100.00

5. Conclusions

This research proposes a model for evaluating the SVA in urban residential buildings using MCDM approaches. This is based on spatial analysis and combined AHP and GIS approaches. The advantage of adopting the outlined techniques is the incorporation of knowledge of geotechnics and structures to generate a map of seismic vulnerability for Tabriz city as a case study. Nine zones of Tabriz city were investigated in terms of two groups of parameters including several sub-parameters. The Analytic Hierarchy Process (AHP) was used to determine the weight of the sub-factors belong to the two groups of parameters. The weights and scores were based on the judgments and preferences of the authors. Therefore, it would not allow for misinterpretation or misjudgment of the weights or scores. Finally, nine zones of Tabriz were divided based on low, very low, moderate, high and very high vulnerability; they were displayed in the form of GIS maps. The application of the developed vulnerability assessment methodology indicates that an urban area may have various vulnerability patterns in terms of geotechnical and structural. According to the results, the geotechnical factor has the highest contributions to the seismic vulnerability assessment of residential buildings. However, factor and its sub-factors differ in nine zones of Tabriz city. The findings revealed that the highest vulnerable zones are zones 5, 4 and 1 in the northeastern part of Tabriz city. However, other parts of Tabriz city have comparatively lower to moderate vulnerabilities to earthquakes. The review of the developmental and master plans of the study area show that the expansion of Tabriz city is in the direction of the North Tabriz Fault (NTF). Hence, large parts of once marginal areas and informal settlements are currently situated in the vicinity of the fault. Therefore, unregulated construction projects akin to mass-housing and lack of construction monitoring in marginal settlements point to the lack of attention to the dangers posed by the faults and other concerns. Furthermore, the narrow passages and anomalies present in zones 5, 4, and 1, poor quality of materials used in construction, lack of spaces and poor access to relief centers critically exacerbate the conditions. Tabriz city deserves special consideration not only for local authorities but also the national government to reassess current strategies for managing natural disasters. Such results provide an appropriate guide for city managers and decision-makers to perceive the influence of each parameter in the SVA of residential buildings and to realize the critical deficiencies in each zone that need to be improved in risk reduction programs. The results also indicate the lack of proper distribution of spaces in Tabriz city and the lack of adequate open spaces such as parks and open spaces there. The AHP/GIS approaches used in this research proposes a practical and effective evaluation of physical seismic vulnerability and provides valuable information for assisting urban planners during mitigation and preparatory phases in many other urban areas around the world.

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