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ORIGINAL PAPER

Earthquake damage modeling using cellular automata and fuzzy rule-based models

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Abstract
An earthquake exhibits a spatially dissipative dynamic system that evolves towards a critical state with no characteristic spatio-temporal scales. In such a system, any weak and local perturbation triggers a cascade of bigger events that can cause human casualties and damage to built environment. In addition to structural elements in buildings, the transmission of earthquake induced forces to the base structure is an essential factor for ground-motion hazard assessment. In this study, we investigated the relationship between soil type and geological structure, and the magnitude of forces transmitted to building structures. We employed cellular automation method to model the process of force transmission to buildings. Using CA, we applied attenuation coefficients of soil to the forces released by fault slip and estimated by Coulomb software. Based on the resultant forces, we further used a fuzzy rule-based model to perform earthquake vulnerability analysis for building structures in the city of Tabriz. The rules embedded in our model included the location of fault line, geologic structure of soil, ground slope, and the number of floors. We minimized vulnerability as a function of the potential losses from earthquakes including death or injury of people, and damage to physical structures. Based on the analysis, we associated a vulnerability grade to different city areas ranged from one to three, indicating low-risk and high-risk regions, respectively. Our results showed that, for earthquakes of low magnitudes, the ground slope and the number of floors in a building are not essential criteria for vulnerability assessment. In the case of large earthquakes, however, by increasing these parameters, the vulnerability grade drastically increases from high to very high-risk range. Finally, for both ground slope and number of floors evaluations in case of a 7-magnitude earthquake, our analysis revealed an expected critical damage near the fault, up to a radius of about 4 km. Our vulnerability maps provide essential knowledge which can mitigate the risk to built environment through making right policies regarding the location, geometric and structural characteristic of buildings, and land-use planning.

Keywords Cellular automata · Earthquake · Fuzzy rule-based logic · Zoning map, Vulnerability

Introduction

The occurrence of natural disasters, especially in urban areas, causes a lot of casualties and financial losses. An earthquake exhibits a spatially dissipative dynamic system that evolves towards a critical state with no characteristic spatiotemporal scales. Most of the damaging effects of the earthquake are caused by the creation of urban structures near the fault (Abedini and Moghimi 2012). In particular, Iran is considered to be an earthquake-prone country due to the populated cities on the fault. On average, a strong earthquake occurs every 7 years here, with high financial and life losses. In 1780, the largest earthquake occurred in Tabriz, a city with the most dangerous faults in Iran, known as the North Tabriz Fault.

Many factors such as the depth of earthquake, distance from the epicenter of an earthquake, type of the layers of earth, shape and mode of the propagation of forces, faults present in the area, groundwater level, and others have a direct role in determining the extent of vulnerability.

Since the status of each cell in the cellular automata depends on its neighboring cells as well as the function of a relationship between each cell and its adjacent cells, so defining the type of such relationship and the number of neighbors can be considered one-dimensional or two-dimensional. They have a direct effect on the function of the cellular automata.

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One of the most important of these effects is how the force propagates and how it is affected by the soil. Therefore, in this study, a cellular automaton was used to model the effects of the soil type on stresses and stresses were propagated. In addition, it should be noted that most of the factors affecting earthquake destruction do not follow a definite law and they are complex, so a rule-based model is used to express these uncertainties and predict the vulnerability. The GIS technology has an important role in providing maps of each of these influential parameters, and MATLAB is another powerful application uses for computing and processing related research.

Various studies have been conducted using different methods and data to determine the vulnerability of urban areas prior to an earthquake (Lantada et al. 2009). Maleki and Movadat (2013) evaluated the spectrum of seismic vulnerability in Yazd based on different intensity scenarios using the Dμ, TOPSIS, and GIS models. The results show that for earthquakes with intensity greater than 7 on the Richter scale, more than 50% of the buildings in the area are vulnerable to earthquakes (Maleki and Movadat 2013). Nyimbili et al. (2018) analyzed earthquake vulnerability using an integration of GIS, AHP, and TOPSIS. In this study, the MCDA techniques of AHP and TOPSIS were both applied to generate earthquake hazard map results for the case study area of Küçükçekmece in Istanbul. Five parameters in this study were determined: topography, distance to epicenter, soil classification, liquefaction, and fault/focal mechanism. Vulnerability and elements at risk analyses were also conducted using population and building data to estimate the potential impacts of earthquake effects especially in the most hazardous regions. The results of AHP and TOPSIS maps show that about 47.3% of the total population and 44.7% of total number of buildings have high vulnerability (Nyimbili et al. 2018). Hossein Nazmfar conducted a study to map evaluation of urban vulnerability against earthquake using an integrated approach of the analytic network process and fuzzy model. Number of floors, age of building, ground area of building, geological formation, and building density are the factors that are considered in this study. The results of this study shows that if earthquake occurs, in district 9 of Tehran, 19.46% and 10.69% of buildings respectively have minor and low vulnerability, while 50.29% of buildings have medium vulnerability. Also, 17.62% and 1.91% of building have high and very high vulnerability respectively, or they are completely damaged (Nazmfar 2019).

Şen and Ekinci (2016) performed a Realization of Earthquake Vulnerability Analysis in Structure Scale with fuzzy logic method in GIS for Kadıköy, Maltepe, and Prince Islands. The analysis shows that 28% of buildings are high risk, 57% are medium risk, and 15% are low risk in these three provinces (Şen and Ekinci 2016). Abedini and Sarmasti (2016) conducted research to predict the vulnerability of the seismic power in the Tabriz fault and to assess the mortality and destruction of the Tabriz metropolitan area by an experimental model with GIS software. The results show that the northern Tabriz fault will experience an earthquake as large as 6.5 on the Richter scale. The losses rate for such an earthquake is estimated to be 1,632,526 people, including 858,123 killed and 774,403 injured (Abedini and Sarmasti 2016). Whereas in previous research, the impact of environmental factors was less considered (Zhang et al. 2015); the main purpose of this study is to consider the impact of the soil type and the ability of cellular automata to model the force propagation process in soil and how soil affects the force.

The purpose of this study is to investigate the impact of each factor separately and determine their impacts in the absence of another factor, after implementing a system that is capable of modeling the point-to-point vulnerability of an area affected by an earthquake.

Material and methods

Study area

The Tabriz metropolis, which is the capital of the East Azerbaijan Province, with a population of about 3,700,000, consists of 10 districts. In terms of the area, it is the second largest city in Iran, with approximately 25 km^2 of the old tissue. The city is developed in the north and south respectively, between the mountains of Eynali and Sahand. According to the topography of the study area, its slope decreases from east to west and opens to the Tabriz Basin. The city of Tabriz is located in the north west of Iran at 1.5° north and 1.5° east. The Tabriz Fault is one of the linear structures of Iran that is traceable 100 km from the Misho Mountains (west) to Bostan Abad (East). The geographical location is shown in Fig. 1.

Data collection

In this study, the stress values were calculated for 5, 6, and 7 earthquakes in Richter scale according to the fault characteristics through Coulomb toolbox in MATLAB. The data of soil attenuation coefficients have also been used, and the factors affecting the earthquake vulnerability have been determined based on research conducted in this field. The earthquake vulnerability was determined and layers of each of these effective parameters were prepared with a 1:116000 scale along with stress values in raster format with Arc GIS software.

Data analysis

Three sections are considered in the design of system: input, processing, and output. The implementation of each section requires the use of a suitable environment and method. Concerning the input section, given the preparation of input data for stresses and layers related to geology, slope, and

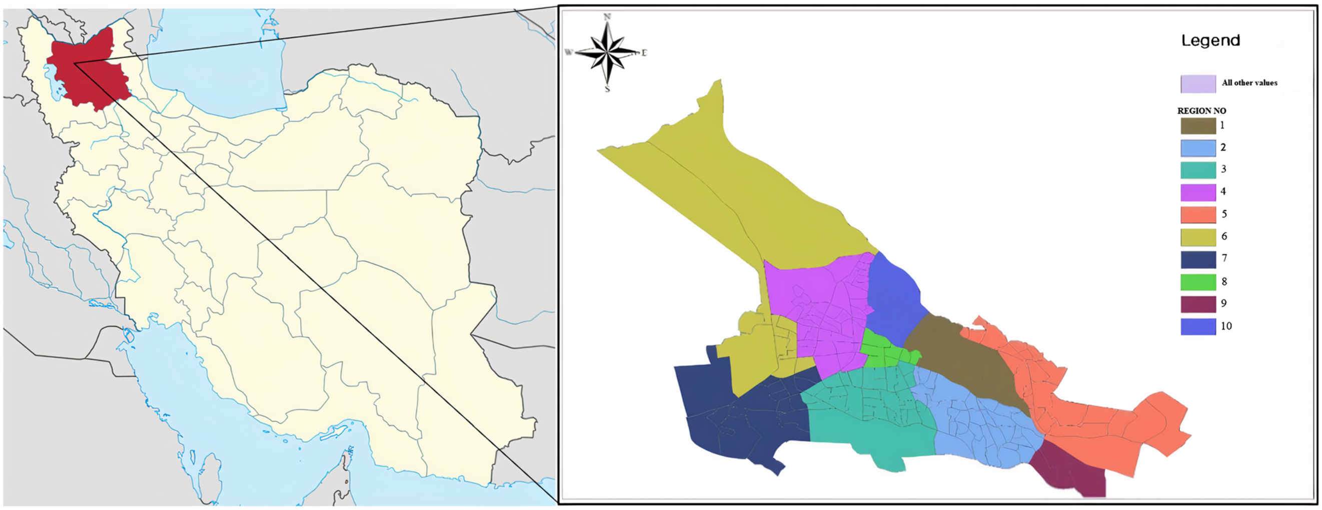

Fig. 1 Geographical location of the study area

number of building floors to be performed separately, MATLAB software is used to prepare stresses and Arc GIS software is used to prepare slopes, floors, and geology layers. Since the process section is the main part of this system, programming in MATLAB has been used for implementation which has been implemented in two separate parts: one is the implementation of cellular automaton and the second is the implementation of a rule-based system.

Finally, the output of the system, given that the results of the analyses are matrix, was used in the MATLAB environment to prepare the result. The region conditions were ranked according to the numbers 1, 2, 3, and 4 where 1 indicates low vulnerability and 2 indicates very high vulnerability. In addition, the amount of destruction per pixel based on the map is determined as output; in this map, the number attributed to each pixel is considered as the amount of destruction in that pixel. In this methodology, rules and regulations are defined based on the experiences and opinions of experts; moreover, rules that are unknown or related to other parameters may exist but are not seen in this collection. Therefore, the more certainty of rules and the more effective the parameters, the greater the certainty increases.

Coulomb stress

Rocks are very slowly, but continuously moving and changing shape. Under high temperature and pressure conditions common deep within Earth, rocks can bend and flow. In the cooler parts of Earth, rocks are colder and brittle and respond to large stresses by fracturing. Earthquakes are the agents of brittle rock failure. A fault is a crack across which the rocks have been offset (Kintner et al. 2019). When an earthquake occurs, only a part of a fault is involved in the rupture. That area is usually outlined by the distribution of aftershocks in the sequence. Generally, the area of the fault that ruptures increases with magnitude (Lay et al. 2017).

It is important to study the focal mechanism parameters of the earthquake because of its critical information for vulnerability analysis earthquake and local study tectonic, regional, and global (Oros et al. 2018). The focal mechanism of earthquakes is geometric representation shifting fractures at the time when the earthquake happens (Nugraha et al. 2019).

Coulomb toolbox is designed to investigate Coulomb stress changes on mapped faults and earthquake nodal planes and focal mechanisms of earthquakes, and is intended both for publication-directed research and for university teaching and instruction.

One can calculate static displacements (on any surface or at GPS stations), strains, and stresses caused by fault slip, magmatic intrusion, or dike expansion. Geologic deformation associated with strike-slip faults, normal faults, or fault-bend folds is also a useful application. Calculations are made in an elastic half-space with uniform isotropic elastic properties following Okada (1992) (Toda et al. 2011). Figure 2 relates to earthquakes of 5, 6, and 7 in Richter scale for Tabriz City are modeled by this software.

Cellular automata

Cellular automatons are discrete dynamical systems whose behavior is based entirely on local communication (Chopard and Droz 1998). Since the status of each cell in the cellular automata depends on its neighboring cells as well as the type of communication function between each cell and its adjacent cells, so defining the type of this relationship and the number of neighbors that can be considered one-dimensional or two-dimensional, has a direct effect on the function of cellular automatons (Weisstein 2002). For example, in the process of modeling stress propagation as one of these parameters, in other words, the starting point of the force and the point at which the force is affected are aligned along a line. In this case, the cells along this line are selected as members that must be evaluated by cellular automata. On the other hand, the

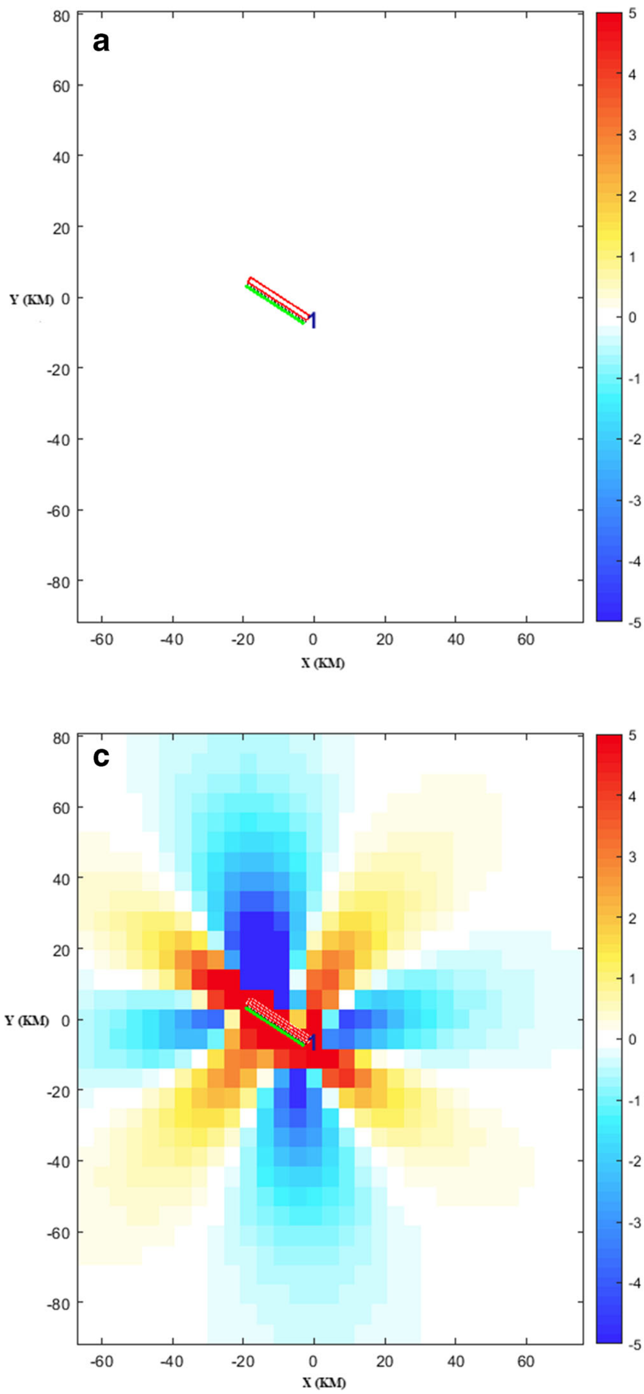

Fig. 2 Coulomb stress variations for the Tabriz strike-slip fault in 10 km depth which the blue is negative bars and red is positive bars of stresses with friction coefficient of 0.4 (**a** 5, **b** 6, and **c** 7 in Richter scale)

definition of diffusion coefficient can determine the relationship of each cell with its adjacent cell, which uses the same cellular automaton process in this study. In this case, the cells along this line are selected as members that must be evaluated by cellular automata. On the other hand, the definition of diffusion coefficient can determine the relationship of each cell with its adjacent cell. In this study, this cellular automaton process was used.

Fuzzy rule-based model

Fuzzy logic has become as a more effective form of logic that can handle the concept of partial truth. Truth here takes intermediate values between "completely true" and "completely false." Fuzzy logic has been used as a modeling methodology that allows easier transition between humans and computers for decision-making and a better method to handle imprecise and uncertain information (Zadeh et al. 1996). This methodology has experienced several developments and is currently widely used in Geosciences studies.

The fuzzy rule-based approach, which is applied here, is based on understandable and verbally formulated rules that are typically expressed as “if-then” clauses (Duckstein 1995). Therefore, Expression data was used to solve problems where it was difficult to quantify by mathematical techniques. Given the above, the importance of using a fuzzy rule-based model in estimating earthquake damage is illustrated. Fuzzy rule-based modeling is particularly effective where the set of rules is significantly simpler than the intended model, meaning that the model is a repeated iteration of a finite number of numerical patterns. Some of the rules are given below:

- If the number of floors is high and the slope is high and the stress is low, then the destruction is equal to low
- If the number of floors is high and the slope is high and the stress is moderate, then the destruction is equal to average
- If the number of floors is high and the slope is high and the stress is high, then the destruction is equal to large
- If the number of floors is low and the slope is low and the stress is high, then the destruction is equal to high
- If the number of intermediate and slope classes is high and the stress is low, then the destruction is equal to low

Earthquake vulnerability analysis

In the earthquake vulnerability study, one of the most commonly overlooked issues is the geological structure of the area and the type of soil by which power transmission operations are performed. The degree of attenuation or in other words the range of forces transmitted to structures on the ground is strongly influenced by the density and type of the soil.

Parameters

Geological features of the area

Tabriz city consists of 6 types of soil layers, and the vulnerability and attenuation coefficients for each of these soil layers are presented in Table 1 ((Toda et al. 2011) and (Costa et al. 2014)). The geological map of Tabriz is shown in Fig. 3.

Slope

Degradation in areas with high slope topography, especially at ridges and peaks, is dramatically increased. Figure 4 is the slope map for Tabriz.

Number of building floors

Previous giant earthquakes have shown that earthquake damage in urban settlements is directly related to the number of floors in the building (Mohammed and Al-Jenaid 2012). In the event of an earthquake that destroys buildings, an increase in the number of floors of buildings will increase the vulnerability. Figure 5 shows the map of the number of building floors in Tabriz.

Results and discussion

Soil attenuation coefficient is one of the effective factors in stress transfer from one point to another. Given that in raster maps, the process of dividing space is used to model continuous spaces, here to model the geological map of the region and the stress maps of each point as pixel maps with considering Tessellation thinking is used to model the environment. On this basis, implementing a cell-based computational method to estimate the amount of stress per pixel can be very effective. Here, as the attenuation coefficient of each pixel causes the amount of force transmitted to the adjacent pixel to be reduced by the damping coefficient, so the amount of stress transmitted to each pixel is obtained by multiplying the damping coefficient by the stress value of that pixel, it comes.

The amount of stress transferred to each cell = the attenuation coefficient per cell × stress per cell

After the attenuation coefficients were applied via cellular automata and a new matrix of stresses was obtained, a model was defined based on a series of rules to calculate the amount of vulnerability for each of these cells. The threshold laws and regulations were evaluated according to the articles and by-laws of Iran and the region, which are presented in the Table 2 which is for slope, geology unites, and the number of floors (Mohammed and Al-Jenaid 2012; Şen and Ekinci 2016).

Also, to determine the thresholds for stresses, three types of earthquakes for three different intensities at two different depths with three different distances were produced by Coulomb. Table 3 shows stresses which were obtained via coulomb 3 for earthquakes with 5, 6, and 7 magnitude.

Given that three parameters were used in this study, 27 conditions were implemented in MATLAB using the if and or commands, also it is worth noting that more parameters can be added to the system. The work process is shown in Fig. 6.

System evaluation

Three types of scenarios were considered to evaluate the system performance based on the model:

the first scenario was designed to have a slope map for all regions with low, medium, and high slope uniformity to investigate the impact of the slope individually.

Table 1 Lithology criteria and effective sub-criteria in earthquake hazards and soil attenuation coefficients

Attenuation coefficient	Low vulnerability	Medium vulnerability	High vulnerability	Lithology unites
0.041			*	Q^{ft2}
0.195	*			Q^{ft1}
0.20	*			PLQ^{c}
0.103		*		PL^{dt}
0.05			*	M_2^{mg}
0.173	*			M_4^{sm}

In the second scenario, the number of identical floors was considered so that the number of low, medium, and high floors was evaluated in order to study the effect of the number of floors individually.

In the third scenario, both the same number of floors and slope value were considered to investigate the direct effect of stresses individually. The following is a description of these scenarios and the interpretation of the scenario results. Figure 7 is the result of destruction for the city of Tabriz with considering the conditions of slope and the number of floors in low, medium, and high amounts.

The first scenario to evaluate

According to Table 4, which are examples of stresses in a 5-magnitude earthquake, the slope in low magnitude earthquakes had little effect on increasing the amount of degradation, and no change in the amount of degradation was observed in Fig. 7a. On the other hand, in Table 5, which are examples of stresses in a 7-magnitude earthquake, show that with increasing slope values, stresses with a high threshold have a significant increase in degradation. For example, in Table 5, the sample had a large amount of slope and stress, so the number 4 is recorded for vulnerability.

Therefore, the studies show that the slope parameter in low-magnitude earthquakes has no effect on increasing the

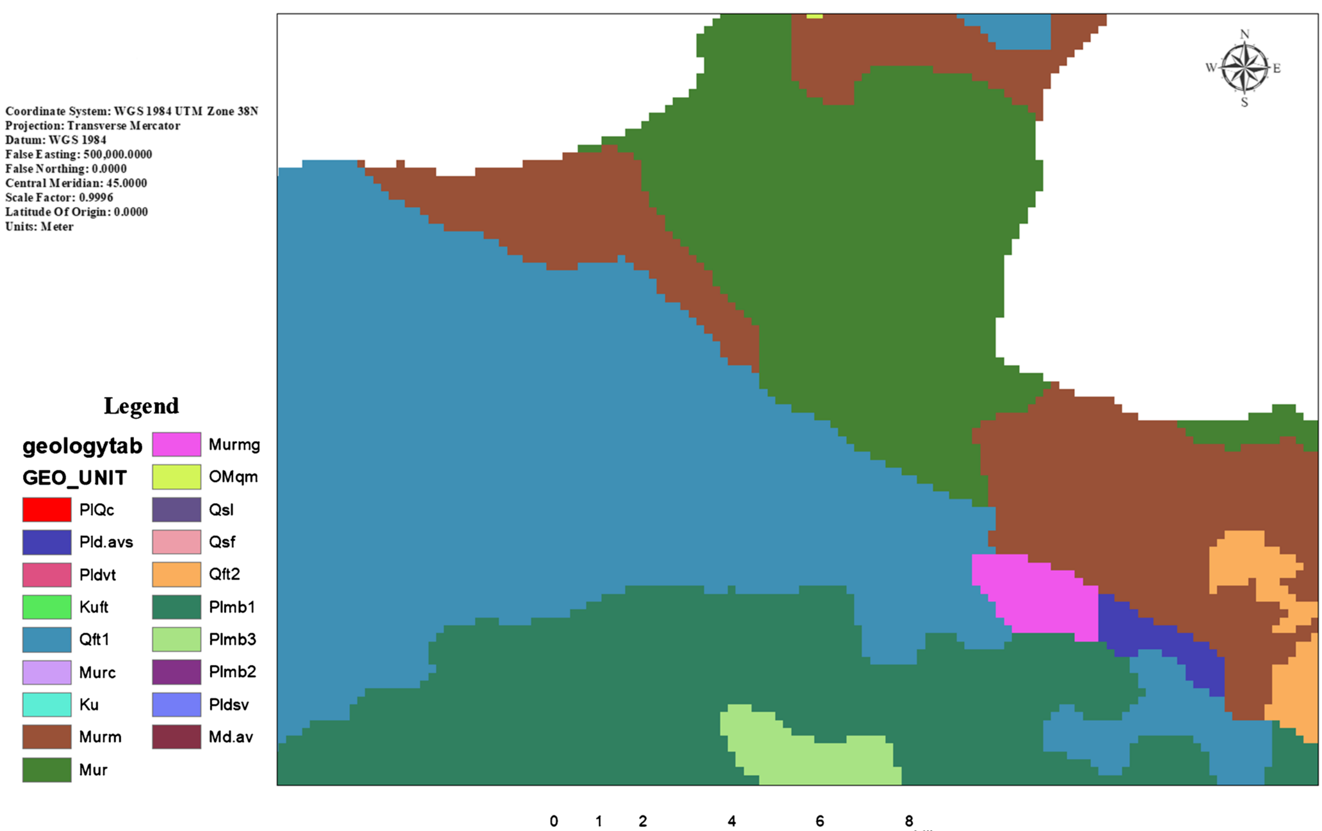

Fig. 3 Geological map of Tabriz City

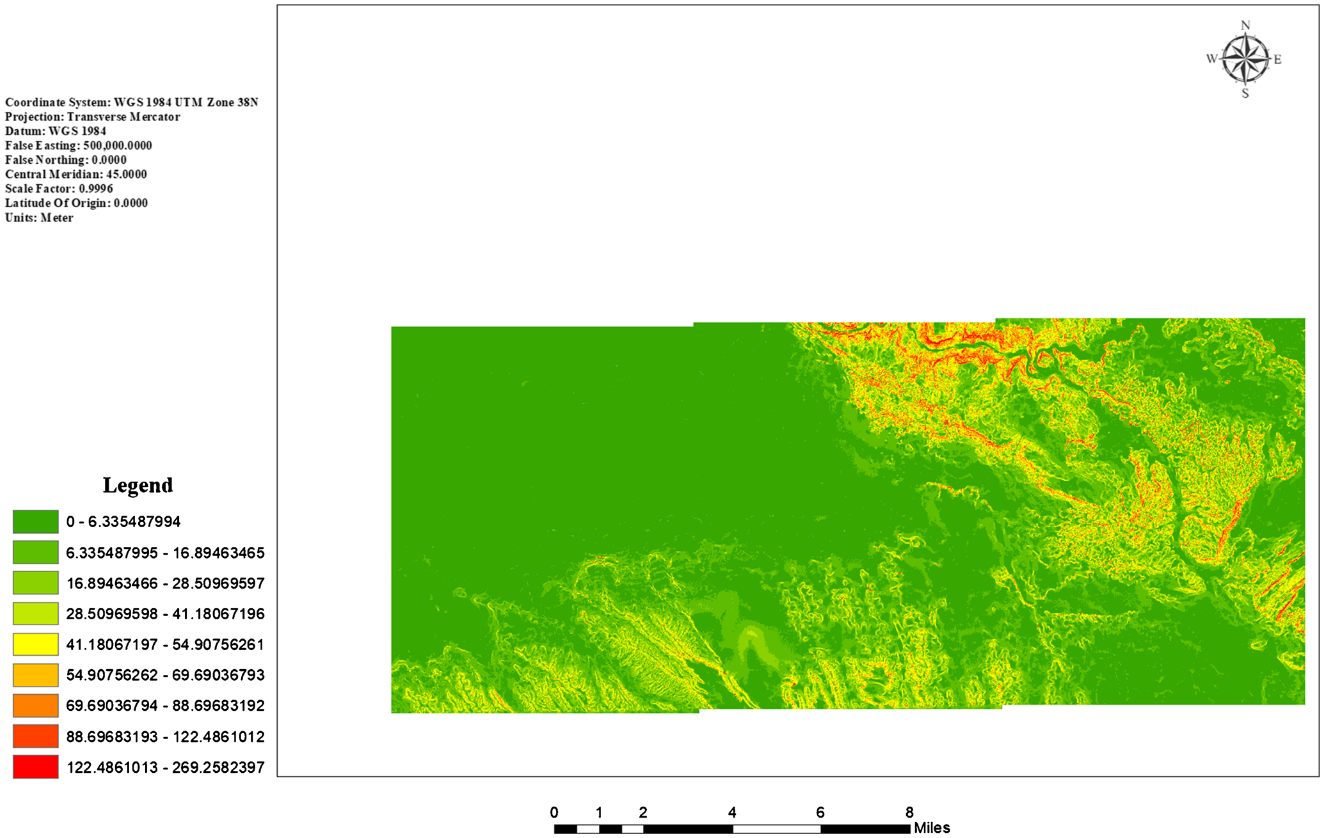

Fig. 4 Tabriz slope map

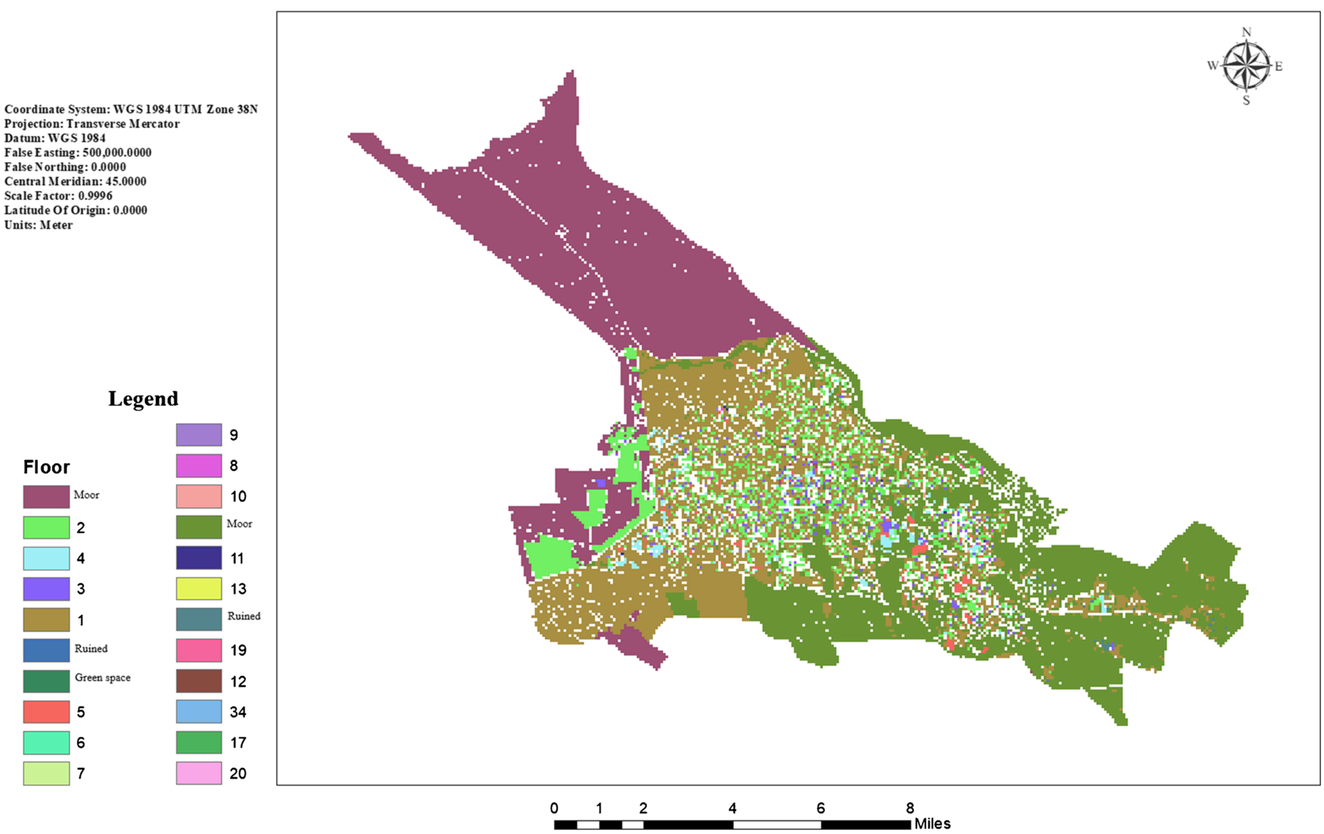

Fig. 5 Map of the number of building floors in Tabriz

Table 2 Parameter of the number of floors, slope, geology unite with amount of vulnerabilities

Over than 5	3–4	1–2	Number of floors
High	Medium	Low	Vulnerability rate
Over than 5	3–4	0–2	Slope value (%)
High	Medium	Low	Vulnerability rate
Young alluvial gullies	Red sandstone and marl	Semi-hard conglomerate	Geology unites
High	Medium	Low	Vulnerability rate

Table 3 Stresses for three earthquakes with different distances to determine threshold

			Distance(km)
	0	5	10
Magnitude(depth = 10 km)			
5	0.136	0.027	− 0.001
6	4.297	0.867	− 0.376
7	48.211	9.727	0.639
	0	5	10
Magnitude(depth = 5 km)			
5	0.187	0.110	0.007
6	18.421	4.953	0.179
7	73.330	19.712	6.276

vulnerability, but in a high-intensity earthquake considered here to be more severe, In the even-slope mode, the damage increases from high (number 3) to very high (number 4).

Figure 7a and Table 4 are for a 5-magnitude earthquake in the same slope state (low, medium, and high):

Figures 7b, c and Table 5 are for a 7-magnitude earthquake in the same slope state (low, medium, and high):

The second scenario to evaluate

Table 6, which is examples of stresses in a 5-magnitude earthquake, show that the number of floors in low-intensity earthquakes has little effect on increasing the amount of destruction, so no change observed in the amount of vulnerability. Also, in Table 7, which are examples of stresses in a 7-magnitude earthquake, show that with increase in the number of floors, stresses with a high threshold have a significant increase in destruction. For example, in Table 7, the sample had a high number of floors and stress, so the number 4 is being recorded for vulnerability.

Therefore, the results show that the number of floors parameter in low-magnitude earthquakes has no effect on increasing the vulnerability, but in a high-intensity earthquake

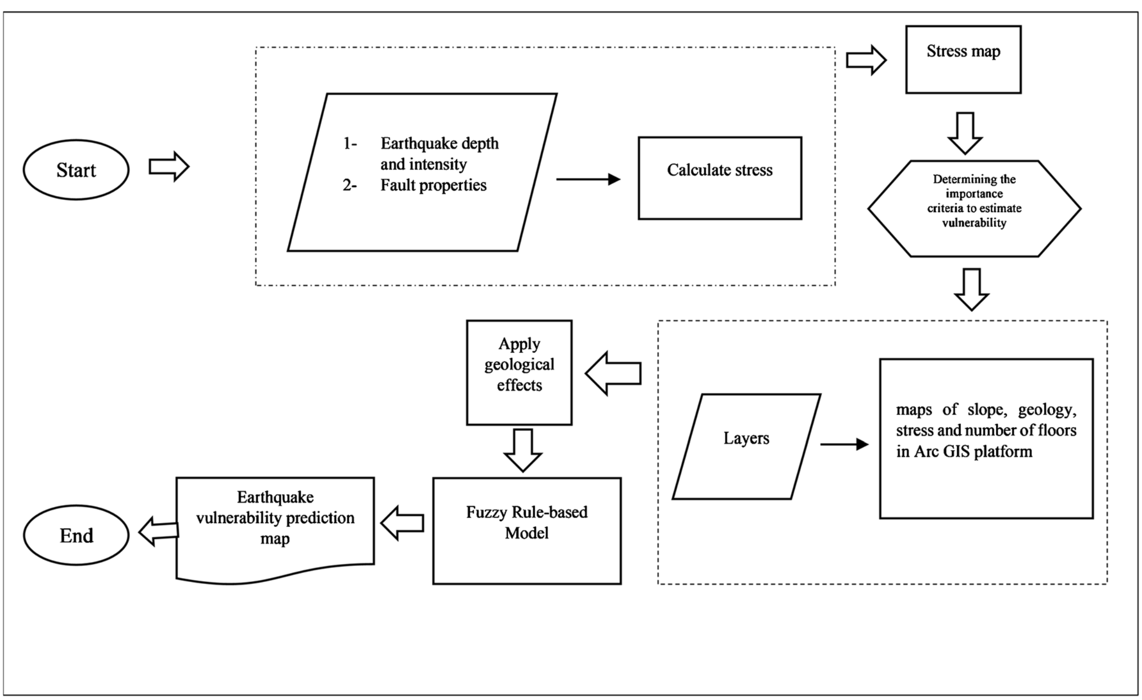

Fig. 6 Flowchart for proposed methodology used in this study

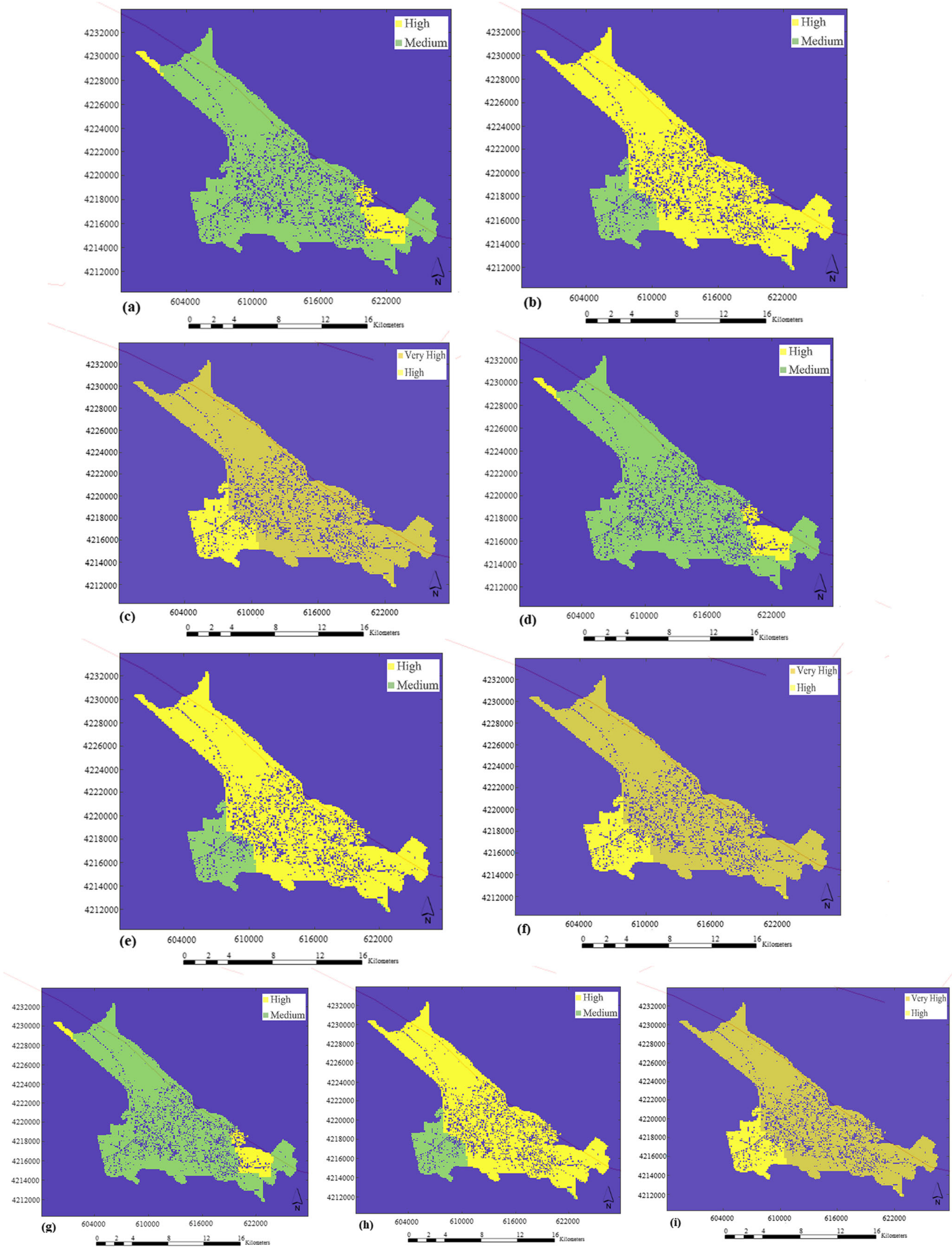

Fig. 7 Destruction for the city of Tabriz with considering the status of slope and the number of floors in low, medium, and high amounts

Table 4 Samples in the same slope state (5 Richter)

Destruction	Number of floors	Slope	Stress	Area number	Sample number
Sample specifications (the same-low slope)					
2	2	1	7.9030	(112,149)	1
2	5	1	7.9030	(113,149)	2
2	2	1	8.9363	(114,149)	3
2	5	1	8.9363	(115,149)	4
Sample specifications (the same-high slope)					
2	5	14	5.7425	(103,186)	1
2	5	14	5.7425	(104,186)	2
2	5	14	5.8157	(105,186)	3
2	5	14	5.8157	(106,186)	4
Sample specifications (the same-medium slope)					
2	4	4	5.1380	(99,167)	1
2	5	4	5.2113	(100,167)	2
2	3	4	8.9044	(153,150)	3
2	14	4	8.9044	(154,150)	4

considered here to be more severe (7 Richter). In the same number of floors mode, the damage increases from high (number 3) to very high (number 4).

Figure 7d and Table 6 are for a 5-magnitude earthquake in the same number of floors state (low, medium, and high):

Figure 7e, f and Table 7 are for a 7-magnitude earthquake in the same number of floors state (low, medium, and high).

The third scenario to evaluate

In this scenario, both the number of floors and the slope value were considered identical in three state of low, medium, and high to evaluate the effect of stresses. The results were that in low-magnitude earthquakes, there was no change in the amount of vulnerability due to the less severe stresses. On the other hand, in the very high-magnitude earthquakes, which 7 Richter is modeled here, with the same amount of slope and number of floors as being within the high threshold, caused a large amount of damage (by number 3 in sample 4) to a very high (by number 4). Finally, it can be concluded that the role of force in the amount of vulnerability is undeniable and is the main factor in the extent of the vulnerability.

Figure 7g and Table 8 are for a 5-magnitude earthquake in the same number of floors and slope states (low, medium, and high):

Table 5 Samples in the same slope state (7 Richter)

Destruction	Number of floors	Slope	Stress	Area number	Sample number
Sample specifications (the same-low slope)					
3	2	1	34.3386	(112,149)	1
3	5	1	34.3386	(113,149)	2
3	2	1	37.0327	(114,149)	3
3	5	1	37.0327	(115,149)	4
Sample specifications (the same-medium slope)					
2	4	4	16.7079	(99,167)	1
2	5	4	16.7079	(100,167)	2
3	5	4	18.9370	(101,163)	3
2	5	4	18.9370	(100,163)	4
Sample specifications (the same-high slope)					
3	5	14	14.6603	(103,186)	1
3	5	14	17.4644	(104,186)	2
3	5	14	17.4644	(105,186)	3
4	5	14	20.2686	(106,186)	4

Table 6 Samples in the same number of floors state (5 Richter)

Destruction	Number of floors	Slope	Stress	Area number	Sample number
Sample specification (the same-medium floor)					
2	4	3.9528	5.1380	(99,167)	1
2	4	5.5902	5.2113	(100,167)	2
2	4	3.9518	5.1879	(101,163)	3
2	4	5	5.1879	(100,163)	4
Sample specification (the same-low floor)					
2	1	0	7.9030	(112,149)	1
2	1	0	7.9030	(113,149)	2
2	1	1.7678	8.9363	(114,149)	3
2	1	1.7678	8.9363	(115,149)	4
Sample specification (the same-low floor)					
3	1	0	34.3386	(112,149)	1
3	1	0	34.3386	(113,149)	2
3	1	1.7678	37.0327	(114,149)	3
3	1	1.7678	37.0327	(115,149)	4

Figure 7h, i and Table 9 are for a 7-magnitude earthquake in the same number of floors and slope states (low, medium, and high):

Evaluation based on a comparison of crude and environmental stresses:

In this type of assessment, the purpose is to show the effects of soil type on the amount of degradation. To do this, the degradation was achieved using crude stresses, then samples were compared with those when the stresses were affected by the type of the earth. It was found that in the absence of the effects of the earth type, the amount of vulnerability was different. The relevant interpretation is presented in Table 10.

As Table 10 shows, in numbers 1 and 2, because the soil type is older terraces with an attenuation factor of 0.195, the soil hardness caused the damping stress to drop below its crude value before reaching sample 3.

The result of predicting the amount of vulnerability for Tabriz

The evaluation results show that this system works accurate. Finally, after evaluating the model, according to the actual slope, the number of floors and the stresses maps caused by

Table 7 Samples in the same number of floors state (7 Richter)

Destruction	Number of floors	Slope	Stress	Area number	Sample number
Sample specification (the same-medium floor)					
2	4	3.9528	16.7079	(99,167)	1
2	4	5.5902	16.7079	(100,167)	2
3	4	3.9518	18.9370	(101,163)	3
2	4	5	17.7223	(100,163)	4
Sample specification (the same-high floor)					
2	14	5.5902	5.7425	(103,186)	1
2	14	10	5.7425	(104,186)	2
2	14	5	5.8157	(105,186)	3
2	14	5.5902	5.8157	(106,186)	4
Sample specification (the same-high floor)					
3	14	5.5902	14.6603	(103,186)	1
3	14	10	17.4644	(104,186)	2
3	14	5	17.4644	(105,186)	3
4	14	5.5902	20.2686	(106,186)	4

Table 8 Samples in the same number of floor and slopes states (5 Richter)

Destruction	Number of floors	Slope	Stress	Area number	Sample number
Sample specification (the same-low number of floors and slopes)					
2	14	14	5.7425	(103,186)	1
2	14	14	5.7425	(104,186)	2
2	14	14	5.8157	(105,186)	3
2	14	14	5.8157	(106,186)	4
Sample specification (the same-low number of floors and slopes)					
2	1	1	7.9030	(112,149)	1
2	1	1	7.9030	(113,149)	2
2	1	1	8.9363	(114,149)	3
2	1	1	8.9363	(115,149)	4
Sample specification (the same-low number of floors and slopes)					
2	4	4	5.1380	(99,167)	1
2	4	4	5.2113	(100,167)	2
2	4	4	5.1879	(101,163)	3
2	4	4	5.1879	(100,163)	4

Table 9 Samples in the same number of floor and slopes states (7 Richter)

Destruction	Number of floors	Slope	Stress	Area number	Sample number
Sample specification (the same-low number of floors and slopes)					
3	1	1	34.3386	(112,149)	1
3	1	1	34.3386	(113,149)	2
3	1	1	37.0327	(114,149)	3
3	1	1	37.0327	(115,149)	4
Sample specification (the same-medium number of floors and slopes)					
3	4	4	49.2315	(148,161)	1
3	4	4	52.5178	(149,160)	2
3	4	4	49.2315	(147,162)	3
3	4	4	49.2315	(148,162)	4

the 7 Richter earthquake, a vulnerability map is obtained as shown in Fig. 8. In the field of earthquake destruction estimation, a study by Abedini and Sarmasti 2016 for Tabriz City have been done, which shows accordance with the results of this study and the accuracy of the results. Figure 8 is related to the results of this study and Fig. 9 is to the research of Abedini and Sarmasti.

Conclusion

Identification of high-risk areas and evaluating the amount of destruction under the influence of parameters such as slope, number of building floors and soil type were the goals considered in this study. Implementation results show that for slope evaluation, in low intensity earthquakes with increasing

Table 10 Comparison of the effect of crude stresses on the amount of degradation with stresses under the influence of lithology (for 7 Richter earthquake)

Sample specification (the same-high number of floors and slopes)					
Destruction	Number of floors	Slope	Stress	Area number	Sample number
3	14	14	14.6603	(103,186)	1
3	14	14	17.4644	(104,186)	2
3	14	14	17.4644	(105,186)	3
4	14	14	20.2686	(106,186)	4

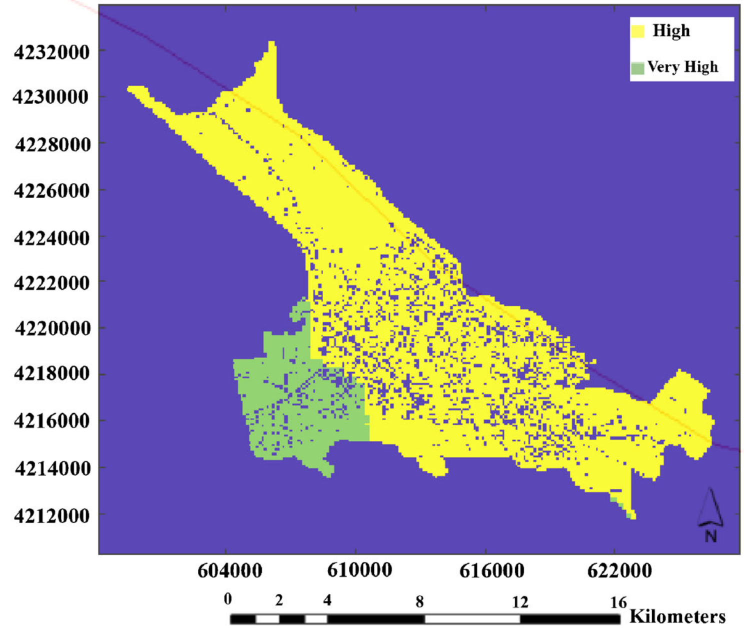

Fig. 8 7-magnitude vulnerability map for Tabriz City

or decreasing magnitude, there is no change in increasing or decreasing the amount of vulnerability while with low, medium and high slope values for low-intensity earthquakes, there is no change in the amount of destruction. But in the case of large earthquakes with increasing slope, there is a significant increase in vulnerability which increases from high to very high.

The parameter evaluation of the number of building floors showed that vulnerability does not change in low-magnitude earthquakes, but in high-magnitude earthquakes modeled in this study, the magnitude of vulnerability increases greatly from high to very high when the number of floors goes up.

In addition, the results of evaluating the combined slope and number of floors to investigate the impact of stresses on

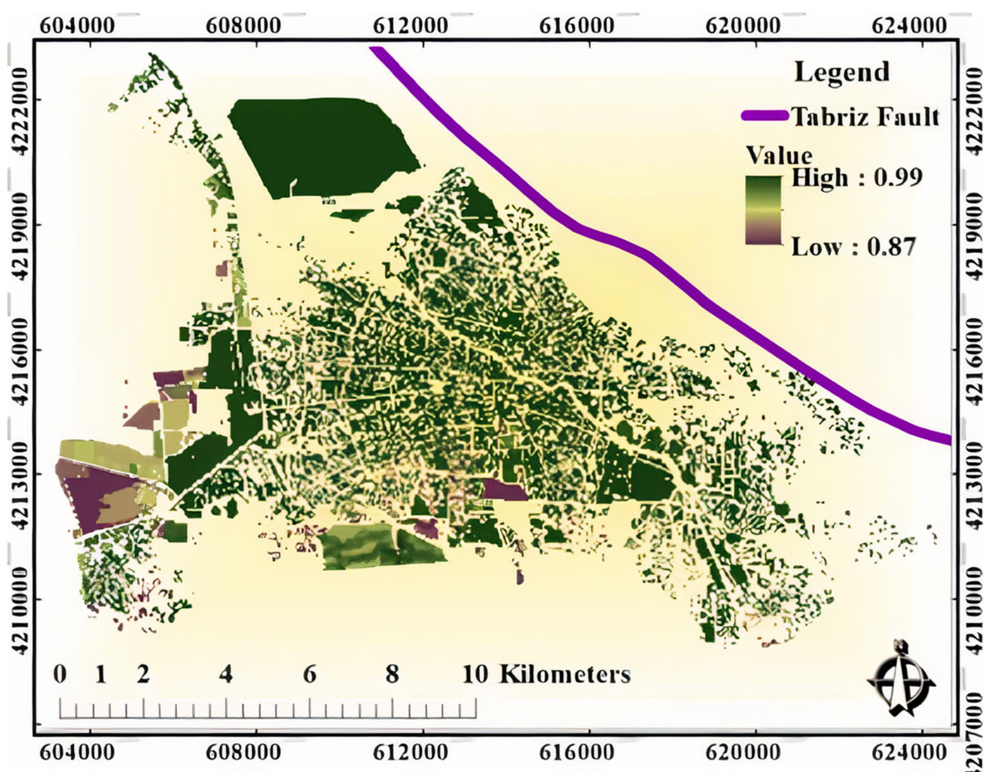

Fig. 9 6.6 Richter demolition map for Tabriz City for validation related to Abedini and et al. (Abedini and Sarmasti (2016))

vulnerability showed that in large earthquakes, slope and number of floors had no significant effect. If the building is just a short distance from the fault, the destruction values for all buildings will be very high, no matter the slope and the number of floors.

Also, by comparing the crude stresses with those applied to the soil attenuation coefficients, it concluded that if the soil properties were not applied to the existing stresses, the prediction results would be very different. It showed that the impact of the soil type in each earthquake plays a crucial role in increasing or decreasing the vulnerability. Considering the results, it was found that the use of cellular automata and rule-based systems in modeling earthquake destruction could have acceptable performance and the results obtained from the system were adapted to the relevant researches. Vulnerability values at different points seem reasonable compared to each other. It is worth mentioning that the method in this study can also be used to model the damage caused by other large explosions at close distances, analysis of groundwater model uncertainty (Abebe et al. 2000), control of water levels in polder areas (Lobbrecht and Solomatine 1999) with considering some additional parameters.

Recommendations for future work

Suggestions that can be used in future work are as follows:

1. In order to improve the system and improve the accuracy of the work, it is recommended to consider more effective parameters in predicting earthquake damage in later stages.
2. In addition to the cellular model used here, it is recommended to use models that consider the impact of the type of structure on the amount of earthquake-induced damage.

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