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Practical seismic resilience evaluation and crisis management planning through GIS-based vulnerability assessment of buildings

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Abstract: The objective of this paper is to demonstrate how assessment of seismic vulnerability can be effective in protection against earthquakes. Findings are reported from a case study in a densely populated urban area near an active fault, utilizing practical methods and exact engineering data. Vulnerability factors were determined due to technical considerations, and a field campaign was performed to collect the required data. Multi-criteria decision making was carried out by means of an analytical hierarchy process including a fuzzy standardization. Earthquake scenarios were applied through an implicit vulnerability model. GIS was utilized and the results were analyzed by classifying the state of vulnerability in levels as very low, low, moderate, high, and very high. Seismic resilience was evaluated as vulnerabilities below the moderate state, being about 40% in an intensity of 6 Mercalli and less than 10% in 10 Mercalli. It is concluded that seismic resilience in the area studied is not acceptable, the area is vulnerable in the expected scenarios, and due to the high seismicity of the region, proper crisis management planning is required in parallel with attempts toward retrofitting. In this regard, an emergency map was developed with reference to the assessed vulnerabilities.

Keywords: seismic resilience; crisis management; vulnerability assessment; earthquake; retrofit; AHP; Expert Choice; GIS

1 Introduction

Earthquake is one of the most destructive natural hazards, and, according to the most recent statisticsm it has the highest death toll compared with other natural hazards, which is caused generally by inadequate seismic protection in urban areas. Although the aseismic design of new buildings is important in mitigating earthquake damage, seismic vulnerability assessment (SVA) of existing buildings is also highly important in this regard. In the literature on SVA, some reports are available of different urban areas, investigated by various methods and levels of data. SVA can, however, be used for the evaluation of seismic resilience (Bruneau *et al.*, 2003; Cimellaro *et al.*, 2010; Kammouh *et al.*, 2018) toward an adequate protection against earthquakes through appropriate planning for crisis management and retrofit-based preparedness. This paper aims at demonstrating the effectiveness of a practical SVA in earthquake protection. The following paragraph summarizes the relevant literature, and the subsequent paragraph describes the main goal and the scope of the research.

The oldest document available relating to the subject reports on research by Emmi and Horton (1993), who explored a methodology for developing earthquake damage forecasts in a geographic information system (GIS) environment through the case study of Salt Lake county, Utah, US. Another remarkable research study was carried out by Cova and Church (1997), who presented a method for modeling community evacuation vulnerability by using GIS. Using GIS for mapping earthquake-related deaths and hospital admissions is also a remarkable related work that was carried out by Peek-Asa *et al.* (2000). The most related document, however, is an interesting article by Rashed and Weeks (2003) that reports findings from a project in which GIS methodology was developed to assess vulnerability through a spatial analytical procedure. The work was aimed at paving the ground for disaster managers, analytical hierarchy process (AHP) was adopted, and it illustrated how a spatial analytical approach can be incorporated into a GIS in order to provide measures of urban vulnerability. Erdik *et al.* (2003) also used GIS to assess the risk of earthquakes in Istanbul, Turkey. A similar study was

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carried out by Codermatz *et al.* (2003) for a region in northeastern Italy. Guan *et al.* (2006) applied GIS to earthquake and tsunami emergency work for seaside cities. Tang *et al.* (2009) also used GIS for emergency assessment of seismic landslide susceptibility through a case study. They adopted the AHP method because of its precision and easy implementation. It has been shown that the assessment will help decision makers to select safe sites for emergency placement of refugees and to plan for future reconstruction. Vicente *et al.* (2011) assessed seismic vulnerability and risk for the historic Coimbra city center in Portugal through the assessment of 679 valuable old buildings using GIS. Meshkini *et al.* (2013) used fuzzy logic and inverse hierarchy process within GIS for seismic assessment of old fabric in Iranian cities. Panahi *et al.* (2014) used AHP and GIS for SVA of school buildings in Tehran, Iran. Shakya *et al.* (2015) assessed the seismic vulnerability of Pagoda temples in Nepal with GIS and showed that Pagoda temples are vulnerable even to low intensities. GIS and AHP have similarly been used by Fallah *et al.* (2015) for SVA of a district in the historic city Yazd, Iran. It has been shown that 81% of the district has medium to high vulnerabilities. Wang *et al.* (2016) presented a GIS-based approach for renewable energy planning to support post-earthquake revitalization. In a different approach, Parsons *et al.* (2016) proposed a conceptual framework for the assessment of disaster resilience. Sadrykia *et al.* (2017) used GIS for SVA in areas with incomplete data and demonstrated that the AHP model has acceptable strength. Another remarkable example of the application of GIS to SVA is a work by Ferreira *et al.* (2017) for the analysis of the impact of retrofitting strategies. Hashemi *et al.* (2017) also used GIS for seismic source modelling, and Alizadeh *et al.* (2018) used GIS and AHP for SVA of residential buildings. Liu *et al.* (2018) used three-stage data envelopment analysis to evaluate the earthquake resilience of counties in China. Didier *et al.* (2018) proposed a compositional demand/supply framework to quantify the resilience. These are only some sample works among many others. SVA of buildings to various earthquake intensities by Nazmfar *et al.* (2019), investigation of resilience in structures and infrastructure by Farsangi *et al.* (2019), different studies on SVA by Kassem *et al*. (2019, 2020a and 2020b), and interesting investigations on resilience evaluation by Sun *et al.* (2019) and Yu *et al.* (2019) can be regarded as remarkable examples of the most recent works.

The review summarized above reveals that SVA is an active area of research in the field of earthquake engineering, GIS is preferred for practical assessments, AHP is well-accepted for precise multi-criteria decision making, and adequate data are required for a reliable SVA. Some of the references also provide suggestions toward using SVA for post-earthquake planning. The research reported in this manuscript, in this regard, was aimed at exploring the usefulness of SVA for seismic resilience evaluation and crisis management planning. This contribution to further understanding the capabilities of SVA benefitted from a conceptual framework proposed for simplified resilience evaluation, a case study in a densely populated urban area near to an active fault, and a field campaign for collecting the required adequate data. Section 2 identifies the case study and describes the research methodology. Section 3 deals with the determination of vulnerability factors, the data collection, and the earthquake scenarios. Section 4 details the assessment and its results. Section 5 translates the assessment results into resilience evaluation and presents a plan suggested for the crisis management. Concluding remarks are given in section 6.

2 The case study and the method of research

North Tabriz Fault (NTF) is one of the most important active tectonic structures in the world, which has caused major earthquakes that have resulted in historic catastrophes by destroying parts of Tabriz city and its surroundings. Table 1 is a summary of the most important earthquakes occurring in the region. The region, in this regard, is characterized with the highest seismic risk. There are also some other seismogenic structures in the region, but NTF is most referred to in the literature due to its prominent role in the seismicity of the region.

The city of Tabriz is located in the northwestern corner of the Iranian plateau and in the central part of the East Azerbaijan province. Tabriz is the capital of the province and includes 10 municipal districts. District 6 is located in the northwestern part of the city, with important industrial plants, different workshops, the airport, and part of the railroad system. According to the latest geo-political divisions of the country, this district includes also a town known as Anakhatoun, which has not been studied in previous SVA studies, although it is a densely populated area located in the vicinity of NTF and neighbors the infrastructure and important locations mentioned above. For this reason, this area (the Anakhatoun town) was selected as the case study in the research being reported. Figure 1 shows the case study area.

The method of the research can be described in 10 steps. Step 1 is the determination of the vulnerability factors, which were determined based on technical considerations concerning the assessment and are thoroughly discussed in section 3. A field campaign was then performed, as step 2, to obtain the adequate data essential for SVA-based research. The engineering data collected were transferred to the well-known Expert Choice software to carry out the multi-criteria decision making of SVA by means of AHP, which forms step 3 of the research. GIS environment was then utilized, as step 4, to create the assessment layers, and fuzzy standardization was applied (step 5) to obtain the precise weighted assessment layers. A preliminary evaluation was executed, as step 6, followed by the application of the site-specific earthquake scenarios (step 7) through an implicit vulnerability model explained in section 4. Vulnerability was accordingly assessed in step 8, which mainly integrated the weighted vulnerability factors with the earthquake scenarios. Finally, seismic resilience was evaluated (step 9) using a simplified conceptual framework, and, as reported in section 5, a plan for crisis management that includes an emergency map was proposed (step 10) with reference to the assessed vulnerabilities.

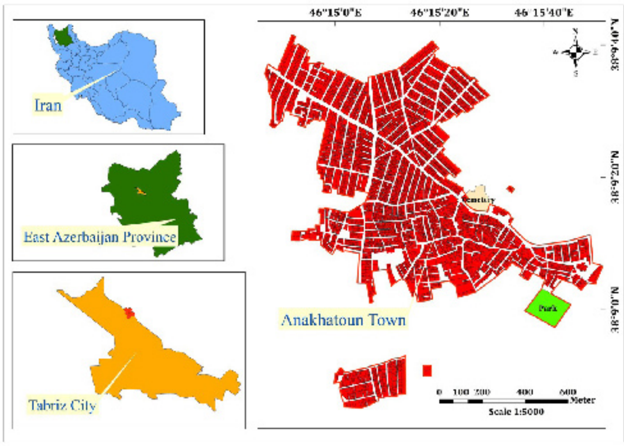


Fig. 1 Area selected for the case study of the research (Anakhatoun town in Tabriz city, East Azerbaijan, Iran)

3 Data preparation

Many different factors can affect seismic vulnerability. The effective factors can be determined based on technical considerations concerning assessment. The factors with regard to the urbanization and construction characteristics of the area studied that are determined to be effective in this research are as follows: (1) construction materials, (2) building age, (3) distance from the closest active fault, (4) soil type of the site, (5) number of stories, (6) floor area ratio, (7) building coverage percentage, (8) building use, (9) neighborhood, and (10) street width. A field campaign was performed to collect the required data and the results are reported in sub-sections 3.1 to 3.10, including also the discussions on the importance of the factors and their sub-factors. Similarly, the earthquake scenarios were defined based on the related considerations. Since the area selected for the case study is mainly affected by the NTF, and it is capable of producing a magnitude 7 earthquake due to the prominent seismic characteristics, the earthquake scenarios have been defined as the intensities equal to VI, VIII, and X in the well-known modified Mercalli scale. For brevity these scenarios are hereafter referred to as 6, 8, and 10 Mercalli, respectively.

3.1 Construction materials

Different materials can be used for the construction

Table 1 A summary of the earthquakes occurring in Tabriz and its surroundings

No.	Date	Epicenter		Magnitude (M_W)	Depth (km)	Reference
		Latitude°	Longitude°			
1	858	38.10	46.30	6.0	Unknown	Ambraseys and Melville (1982)
2	1042/11/04	38.10	46.30	7.5	Unknown	Ambraseys and Melville (1982)
3	1641/02/05	37.90	46.10	6.8	Unknown	Ambraseys and Melville (1982)
4	1717/03/12	38.10	46.30	5.9	Unknown	Ambraseys and Melville (1982)
5	1721/04/26	37.90	46.70	7.6	Unknown	Ambraseys and Melville (1982)
6	1780/01/08	38.20	46.00	7.7	Unknown	Ambraseys and Melville (1982)
7	1932/08/10	38.3	46.3	4.9	33	IIEES (2020) and IRSC (2020)
8	1960/03/20	38.25	46.00	5.2	0	IIEES (2020) and IRSC (2020)
9	1999/03/02	38.405	46.416	4.7	10	IIEES (2020) and IRSC (2020)
10	2005/06/07	37.99	46.84	4	18	IIEES (2020) and IRSC (2020)
11	2007/12/01	38.23	46.48	4.2	14	IIEES (2020) and IRSC (2020)
12	2010/02/02	37.92	46.98	4.1	14	IIEES (2020) and IRSC (2020)
13	2012/08/11	38.55	46.87	6.1	15	IIEES (2020) and IRSC (2020)
14	2012/08/11	38.46	46.75	4.9	15	IIEES (2020) and IRSC (2020)
15	2012/08/11	38.58	46.78	6.2	16	IIEES (2020) and IRSC (2020)
16	2012/08/14	38.46	46.76	5.2	14	IIEES (2020) and IRSC (2020)
17	2012/08/15	38.45	46.66	5.1	14	IIEES (2020) and IRSC (2020)
18	2012/11/07	38.48	46.57	5.8	14	IIEES (2020) and IRSC (2020)
19	2016/08/02	38.525	46.748	4	18	IIEES (2020) and IRSC (2020)
20	2019/08/16	37.96	46.59	4.2	10	IIEES (2020) and IRSC (2020)

of buildings. Types of material generally used in an urban area depend on various parameters, including economic conditions, environmental conditions, the materials available in the region, the scientific/engineering level of the construction industry in the region, and many others. Most of the buildings in the area studied are buildings with steel structural elements, but there are also some concrete buildings and older buildings made up of sun-dried mud and wood. Figure 2 is the data layer generated in GIS to represent the construction materials factor in SVA.

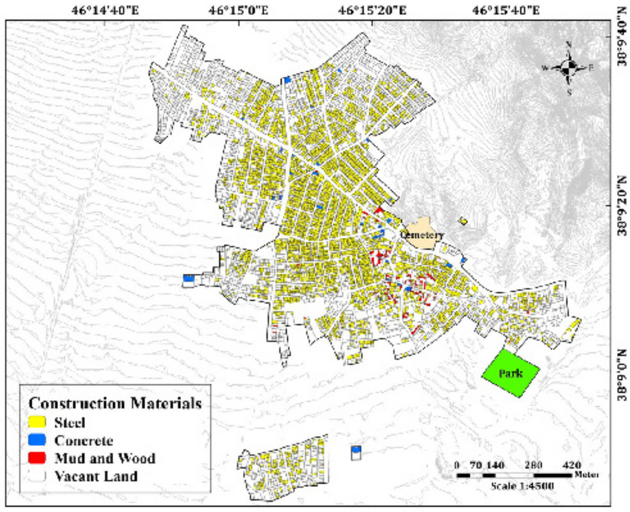


Fig. 2 Data layer generated in GIS to include the construction materials factor in SVA

3.2 Building age

The age of a building plays an important role in its seismic vulnerability. Regarding the quality of construction in the case study area, the progressive advances in the seismic regulations mandated, and some other technical criteria, the data collected from the performed field campaign were used to classify the buildings in 3 categories. This classification is included in the analyses through the data layer shown in Fig. 3. Category 1 (new buildings category) includes buildings with an age of less than 10 years that satisfy most of the up-to-date seismic regulations. Category 2 (old buildings category), in comparison, includes buildings with an age of 10 to 30 years that have been designed and constructed with the previous editions of the seismic codes (mainly the standard referred to as Standard No. 2800). Buildings with an age of more than 30 years, however, are classified in category 3 (pre-norm buildings category).

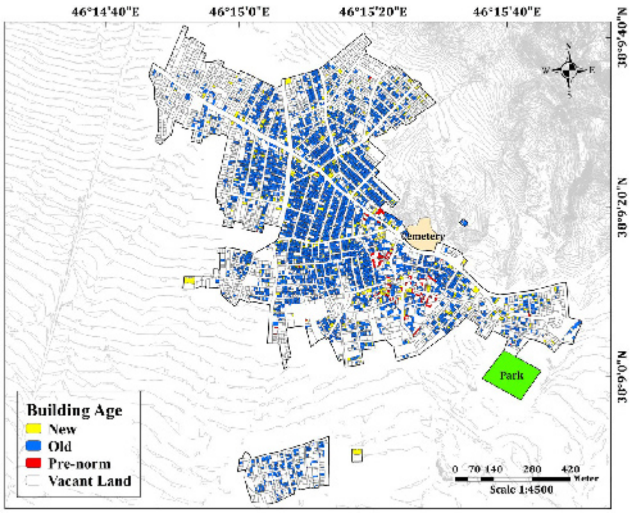


Fig. 3 Data layer generated in GIS to include the building age factor in SVA

3.3 Distance from the closest active fault

Being closer to faults, civil structures are expected to experience more dangerous ground motions that can be richer in high frequencies or can contain long duration large amplitude velocity pulses. When a distance shorter than 15–20 kilometers is generally accepted as near-fault distance, it is also known that peak ground motion parameters can increase significantly for shorter distances in near-fault ranges (Bray and Rodriguez-Marek, 2004; Cheng and Bai, 2017). According to Fig. 4, which represents the latest information published by the Geological Survey and Mineral Exploration Organization of Iran (GSI, 2019) and the Road, Housing and Urban Development Research Center of Iran (BHRC, 2020), the active fault closest to the case study area is NTF. Distances are measured from this fault as the prominent seismic source. Two sub-factors (less than 1 and 1–2 kilometers) are defined to be used in the AHP, which will be discussed in the next section.

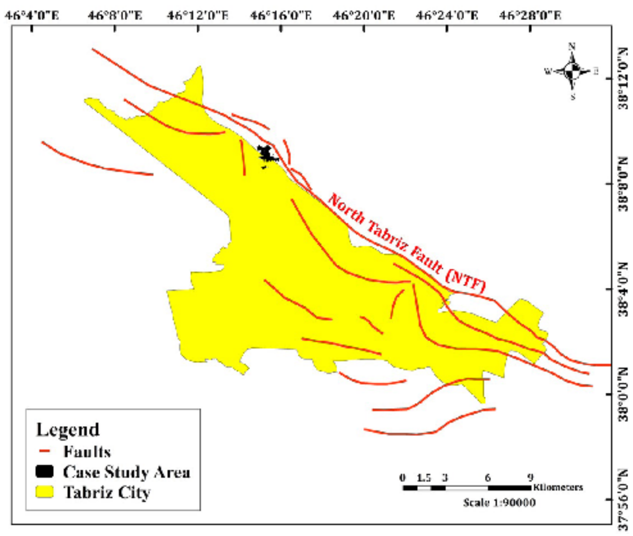


Fig. 4 Faults affecting the seismic vulnerability in the case study area

3.4 Soil type of the site

Soil type of the site has an inevitable effect on the characteristics of the ground motions experienced by buildings and other typical civil engineering structures.

Soil types in different sites of the case study area of the research are classified based on engineering observations, and the data collected through the field campaign are classified into two categories. Figure 5 represents this classification (ST1 and ST2) applied on the map of the case study area, when ST1 (Soil Type 1) and ST2 refer respectively to soil with shear wave velocity of 375–750 m/s and 175–375 m/s.

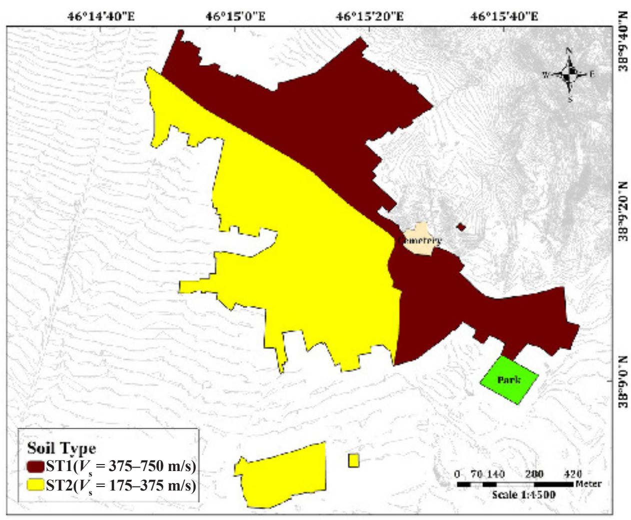


Fig. 5 Data layer generated in GIS to include the soil type factor in SVA

3.5 Number of stories

The number of stories in a building is a good measure of its height, which is important in its dynamic response and the number of people who need to be protected against or rescued after major earthquakes. This is the reason that number of stories is considered as another effective factor in SVA in this research. Figure 6 is the data layer generated in GIS for this factor, with classification of the buildings in the case study area into four groups of 1-story, 2-story, 3-story, and 4^{+}-story.

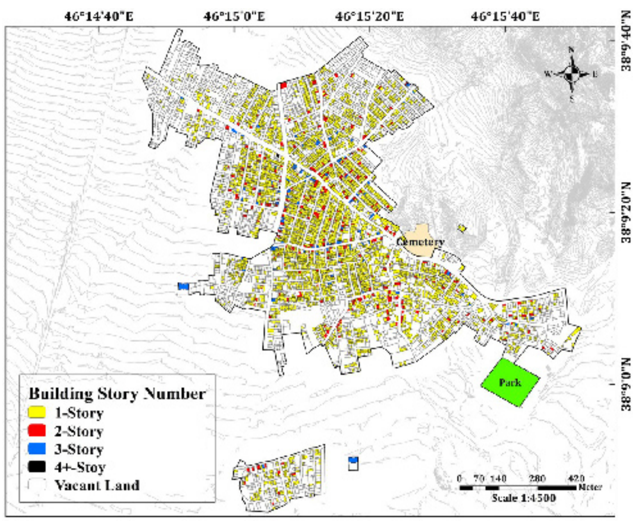


Fig. 6 Data layer generated in GIS to include the effect of number of stories in SVA

3.6 Floor area ratio

Floor area ratio (FAR), which is a much referenced technical criterion in construction industry, is a critical factor also in SVA. FAR can indeed be translated to the amount of wreckage expected after a devastating earthquake. Greater FARs in an urban area, such as the area studied in this research, are equal to further need for deeper search to evacuate people from collapsed buildings, as well as closed streets preventing rescue efforts. FAR, in this regard, is included in the SVA of this research by defining four levels as reported in Fig. 7.

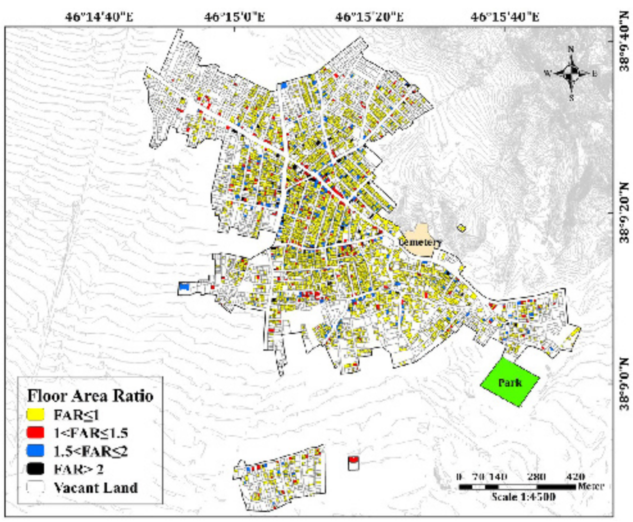


Fig. 7 Data layer generated in GIS to include the effect of FAR in SVA

3.7 Building coverage percentage

The SVA translation of another construction industry characteristic, known as building coverage percentage (BCP), which represents the percentage of the building area to the land area, is the percentage of possibly demolished area to the area available for rescue efforts. BCP is also related to the risk of pounding. It is, therefore, an effective factor in SVA and is included in this research. As shown in Fig. 8, the buildings of the case study area are classified into four categories by BCPs of less than 25%, between 25% and 50%, between 50% and 75%, and between 75% and 100%.

3.8 Building use

Building use has a remarkable role in seismic design, and this is because of the higher importance factors assigned by the design codes to some critical buildings such as hospitals and schools in comparison to other buildings, such as residential buildings. Buildings with different uses will then have vulnerability levels. It will also be useful in crisis management planning to include the effect of this factor in SVA. Figure 9 is the data layer generated in GIS for this purpose.

3.9 Neighborhood

Neighborhood, as well as the BCP, can be used to estimate the risk of pounding between buildings. The number of neighbor buildings sharing their property lines is an important criterion for the estimation of seismic damages related to pounding. The importance of this factor, referred to as neighborhood, increases significantly in crowded urban areas such as the case study area of this research. Neighborhood, in this regard, is the other factor included in the SVA in this research. Details are represented in Fig. 10.

3.10 Street width

The width of alleys, streets, and boulevards (all referred to as street, here) is extremely important in SVA aimed at crisis management planning. Wider streets provide shelter and facilitate rescue. According to Fig. 11, street width in the case study area of the research changes between 4 and 20 meters. The data layer generated is included in SVA, and which will be discussed in the next section.

4 Seismic resilience evaluation through the vulnerability assessment

The data provided in the previous section are included in the assessment process described in this section, where the results are also discussed. As described in section 2, the SVA carried out is based on the application of GIS, Expert Choice, AHP, and a fuzzy standardization. GIS was introduced in the previous section with its first application in the generation of the data layers. The application of Expert Choice, the methods used for multi-criteria decision making, and other details are described in this section.

Vulnerability assessment starts with scaling the factors effective in SVA (as defined in sub-sections 3.1 to 3.10). The fundamental scale used for this purpose is represented in Table 2, which is the well-known Saaty′s scale proposed in 1980 (Saaty and Shih, 2009).

Saaty′s scale, applied on the data prepared for SVA of this research, results in the ranking reported in Table 3 reflecting the judgment carried out through the technical considerations discussed in the previous section and the classification of the state of vulnerability in very low, low, moderate, high, and very high levels. This ranking provides the basis for AHP, which involves following 3 steps: (1) generation of the binary comparison matrix, (2) calculation of the weights, and (3) investigation of the consistency. Experts who participated in the AHP process to provide weights for the factors included in this research come from various related disciplines of urban planning, GIS and Cartography, earthquake engineering, geotechnical engineering, and structural engineering. The binary comparison matrix, which has been generated in Expert Choice for the prioritized factors, is shown in Fig. 12.

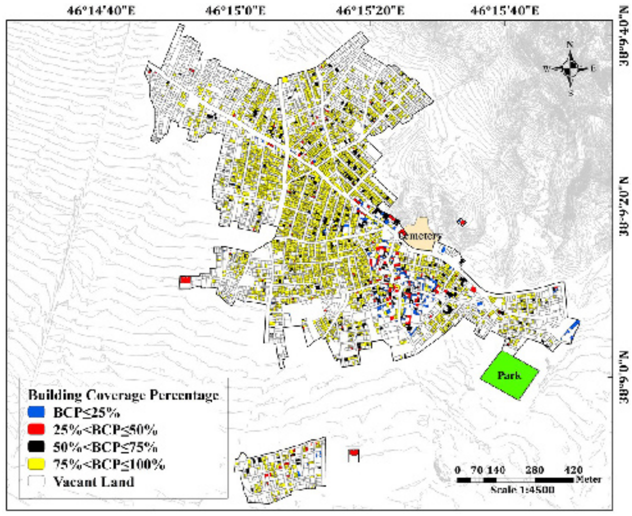


Fig. 8 Data layer generated in GIS to include the effect of BCP in SVA

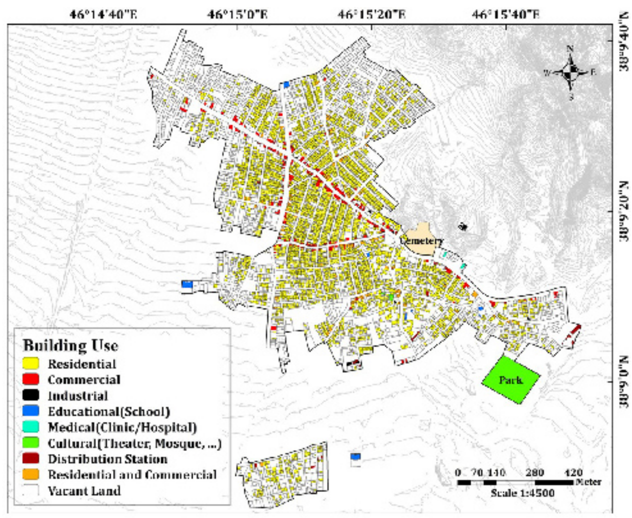


Fig. 9 Data layer generated in GIS to include the effect of building use in SVA

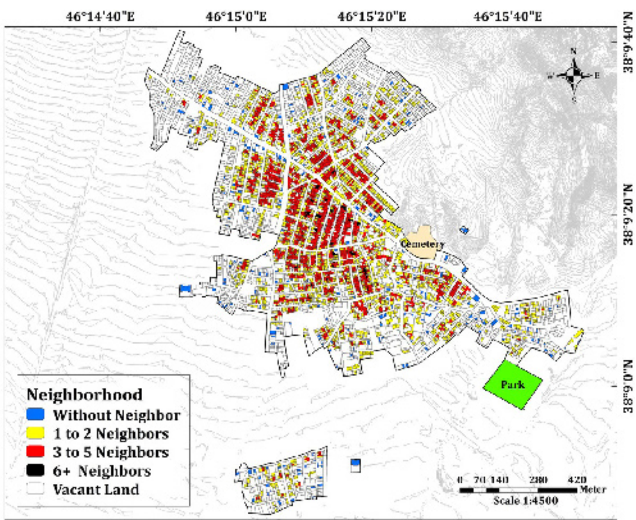


Fig. 10 Data layer generated in GIS to include the effect of the number of neighbor buildings in SVA

Figure 13 shows the weights calculated by Expert Choice. As can be seen, the calculation error is 0.02, which is appropriately acceptable with regard to the inconsistency measure proposed in 2001 by Saaty (as cited by Benitez *et al.* (2011)) requiring a consistency ratio (CR) smaller than 0.1. CR is indeed the ratio between the consistency index and its average value. Based on the Saaty's measure, in the case of a CR greater than 0.1, a new comparison matrix is solicited until CR < 0.1.

Since the CR in the calculation of the weights in this research is equal to 0.02, the results of the AHP executed can now be used for the purpose of assessment. The weights calculated above provide the second part of the data (in addition to the data layers generated in the previous section) required for the vulnerability assessment using GIS. GIS accepts these weights as the multipliers for the corresponding data layers and combines the effects, after the fuzzy standardization, to obtain the basic vulnerability map. In this research, linear membership function of the overlay toolset of the spatial analyst tools of GIS is used for the purpose of standardization. The basic vulnerability map obtained is shown in Fig. 14.

As can be seen, a vulnerability of above moderate level is expected for almost half of the buildings. Figure 15 provides further details about the distribution of the basic vulnerability levels.

In order to apply the earthquake scenarios, a well-accepted implicit vulnerability model proposed by Milutinovic and Trendafiloski (2003) has been used. The model used is suitable for vulnerability assessments in urban environments due to not having detailed site-specific seismicity estimates and micro-seismicity studies but adequate estimates on the seismic intensity. It has widely been used in seismic vulnerability studies (Barbat *et al.*, 2008; Castillo *et al.*, 2011; Abdollahzadeh *et al.*, 2015) and defines mean semi-empirical vulnerability functions (MVFs) that correlate the mean damage grade (μ_D) with the macro-seismic intensity (I) and the vulnerability index (V_I). The MVF used is given in Eq. (1).

$$\mu_D = 2.5\left[1 + \tan h\left(\frac{1 + 6.25V_t - 13.1}{2.3}\right)\right] \quad (1)$$

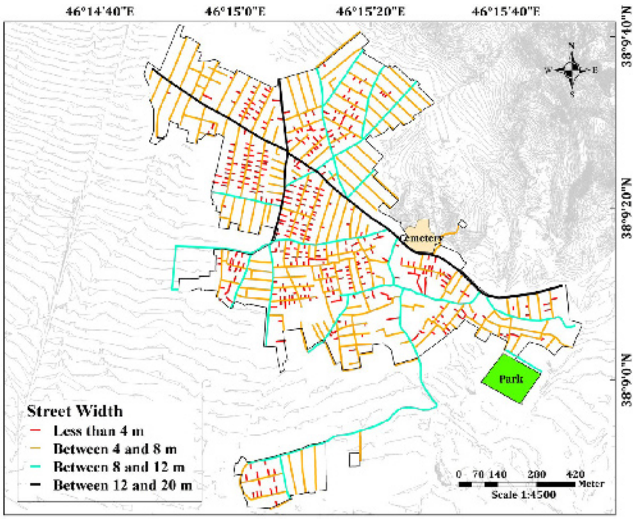
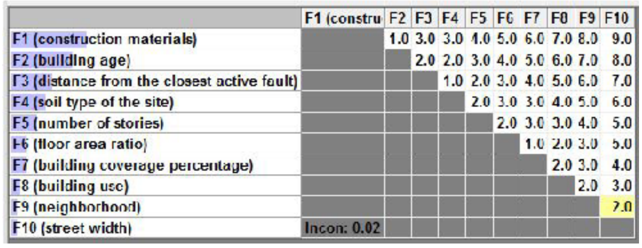


Fig. 11 Data layer generated in GIS to include the effect of the street width in SVA



	F1 (constru	F2	F3	F4	F5	F6	F7	F8	F9	F10
F1 (construction materials)		1.0	3.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
F2 (building age)			2.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
F3 (distance from the closest active fault)				1.0	2.0	3.0	4.0	5.0	6.0	7.0
F4 (soil type of the site)					2.0	3.0	3.0	4.0	5.0	6.0
F5 (number of stories)						2.0	3.0	3.0	4.0	5.0
F6 (floor area ratio)							1.0	2.0	3.0	5.0
F7 (building coverage percentage)								2.0	3.0	4.0
F8 (building use)									2.0	3.0
F9 (neighborhood)										7.0
F10 (street width)	Incon: 0.02									

Fig. 12 Binary comparison matrix generated in Expert Choice

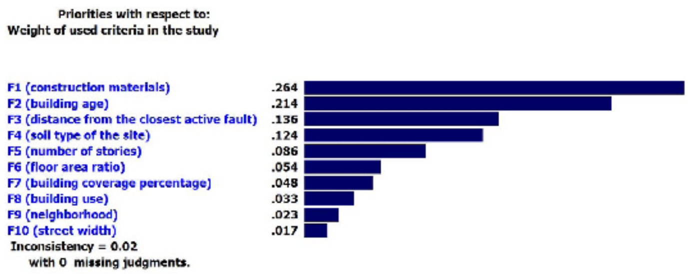


Fig. 13 Weights calculated for the factors included in the SVA

Table 2 Fundamental scale for pairwise comparisons in AHP (Saaty and Shih, 2009)

Rank	Definition
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

The macro-seismic intensities are indeed the intensities defined as the earthquake scenarios in section 3, the vulnerability index is defined through the AHP executed based on the vulnerability parameters discussed in section 3, and the mean damage grades obtained based on the damage thresholds discussed in detail by Milutinovic and Trendafiloski (2003) are included in the SVA carried out by GIS. Figure 16 shows the vulnerability assessed in the 6 Mercalli scenario.

As can be seen, even if the 6 Mercalli scenario is highly probable in the region with regard to its seismicity, as discussed in the previous sections, the number of buildings with a vulnerability of above moderate level is enough to be concerned about the possible higher intensities. The statistics reported in Fig. 17 represent the distribution of the vulnerability levels in this scenario.

The vulnerabilities are below the moderate level only in 42.3% of the buildings.

Vulnerabilities in higher intensities are shown in Figs. 18 and 20, with the explanatory statistical information in Figs. 19 and 21 provided for 8 Mercalli and 10 Mercalli scenarios, respectively.

A comparison between Figs. 16 and 18 shows that the very low and low vulnerabilities in 6 Mercalli scenario are mostly changed to moderate vulnerability in 8 Mercalli. It is also evident from Fig. 20 compared with Fig. 18 that below moderate vulnerabilities are mostly changed to high and very high vulnerabilities in 10 Mercalli. Based on the statistics provided in Figs. 19 and 21, vulnerabilities below the moderate state, which were about 40% in 6 Mercalli, are reduced to about 20% in 8 Mercalli, being less than 10% in 10 Mercalli. This means that the area studied is seismically vulnerable and its resilience to the probable earthquakes is questionable. The next section evaluates the resilience and provides a crisis management plan.

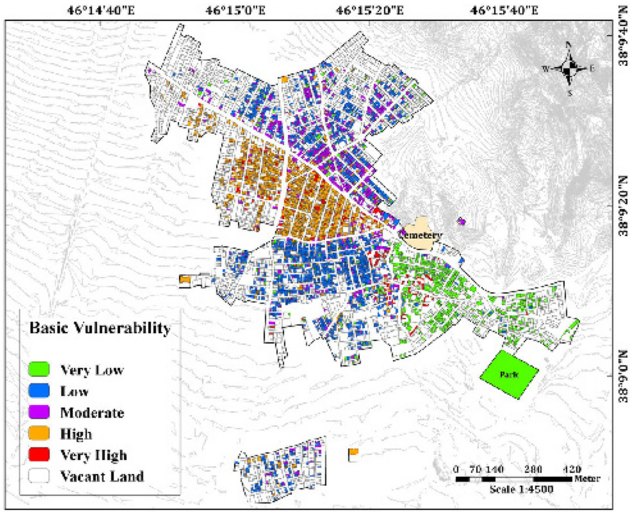


Fig. 14 Basic vulnerability map of the case study area

Table 3 Vulnerability importance ranks of the factors effective in the assessment

Factor	Sub-factor	Vulnerability importance					Factor	Sub-factor	Vulnerability importance				
		1	3	5	7	9			1	3	5	7	9
Construction materials	Steel	•					Building coverage percentage	Less than 25%	•				
	Concrete		•					Between 25% and 50%		•			
	Mud and wood					•		Between 50% and 75%			•		
								Between 75% and 100%				•	
Building age	New	•											
	Old			•			Building use	Residential			•		
	Pre-norm					•		Commercial		•			
								Industrial			•		
Distance from the fault	Less than 1 km					•		Educational				•	
	Between 1 and 2 km				•			Medical					•
								Cultural				•	
Soil type	V_s = 375 – 750 m/s		•					Facilities				•	
	V_s = 175 – 375 m/s			•				Residential/Commercial			•		
Number of stories	1	•					Neighborhood	Without neighbor		•			
	2		•					1 to 2 neighbors			•		
	3			•				3 to 5 neighbors				•	
	4^+					•		6^+ neighbors					•
Floor area ratio	Smaller than 1	•					Street width	Less than 4 m					•
	Between 1 and 1.5			•				Between 4 and 8 m				•	
	Between 1.5 and 2				•			Between 8 and 12 m			•		
	Greater than 2					•		Between 12 and 20 m		•			

5 Seismic resilience evaluation and crisis management planning

Different definitions of seismic resilience, provided by researchers such as Bruneau *et al.* (2003), Cimellaro *et al.* (2010), and Kammouh *et al.* (2018), who were cited in the literature review in the introduction section, can be summarized here as the ability to resist earthquakes and recover in an efficient manner. With this straightforward definition, it is evident that evaluation of seismic resilience involves different elements such as seismic prediction, vulnerability assessment, and downtime estimation (Cimellaro *et al.*, 2010; Farsangi *et al.*, 2019; Yu *et al.*, 2019). Most of the frameworks proposed by different researchers for evaluating seismic resilience quantify seismic resilience based on the assessment of the downtime, requiring a series of calculations. A practical framework proposed and used in this research

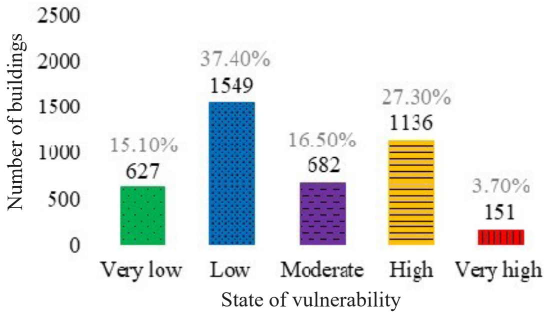


Fig. 15 Distribution of the basic vulnerability levels

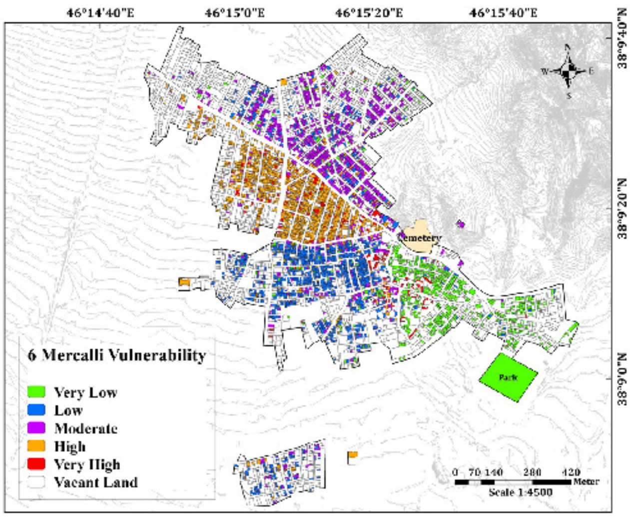


Fig. 16 Vulnerability assessed in the earthquake scenario with modified Mercalli intensity of 6

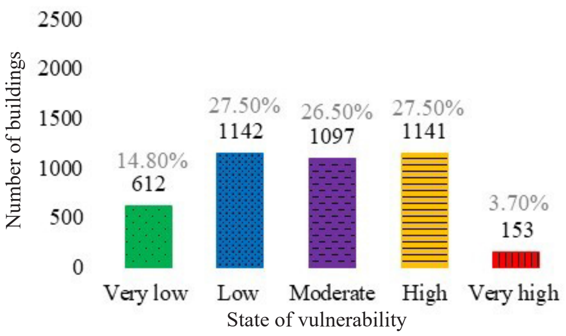


Fig. 17 Distribution of the 6 Mercalli vulnerability levels

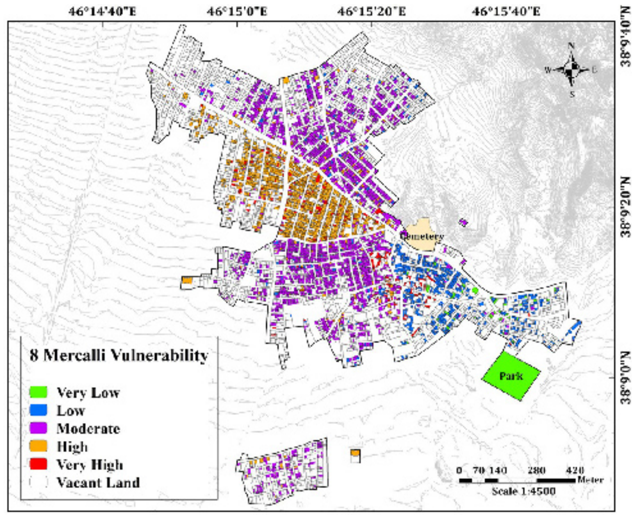


Fig. 18 Vulnerability assessed in the earthquake scenario with modified Mercalli intensity of 8

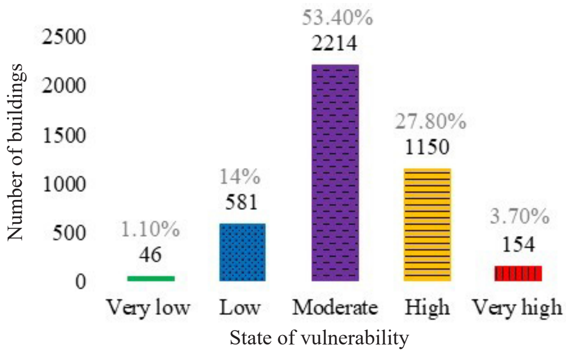


Fig. 19 Distribution of the 8 Mercalli vulnerability levels

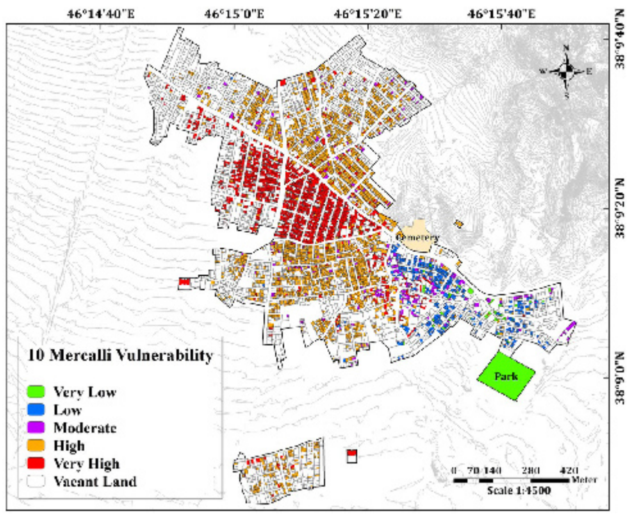


Fig. 20 Vulnerability assessed in the earthquake scenario with modified Mercalli intensity of 10

for the preliminary evaluations and crisis management planning aimed to be carried out for the urban area studied is based on the estimation of the resilience as the inverse of the vulnerability, which is indeed the simplified conceptual version of the quantified concise frameworks. Figure 22 summarizes the results obtained from the SVA that can be translated into a resilience measure through the framework proposed. The first conclusion on this basis is that the seismic resilience is not acceptable, even in a highly probable earthquake scenario (6 Mercalli), when almost half of the buildings have above moderate vulnerabilities (moderate, high, or very high). Second, is the remarkable reduced resistance expected in the higher intensities (8 and/or 10 Mercalli scenarios), when an average 85% of the buildings have above moderate vulnerabilities in these probable higher intensities.

With regard to the low seismic resistance evaluated, crisis management planning is essentially required. Attempts toward retrofitting the vulnerable buildings are welcomed. An emergency map, however, is essential to be prepared against the probable earthquakes. Figure 23 provides the required information for such a map, giving an insight into the post-earthquake availability of the access lines in the area studied. Estimation of fragility is obtained based on the vulnerabilities assessed in Figs. 16, 18, and 20. Higher numbers of the buildings vulnerable around each access line are estimated to result in the fragility of the access line. As can be seen, the access lines are mostly closed in the central part of the area studied, and access lines that are expected to be open for rescue works should be used in a good plan to avoid any problem.

The emergency map shown in Fig. 24, in this regard, locates the critical emergency operation units in the accessible locations based on the judgements obtained by investigating the vulnerability parameters discussed in section 3 and the assessments presented in Fig. 23.

The emergency operations center (EOC) is planned to be located in the sport club in the entrance of the area in the vicinity of the main access line connecting the area to the other parts of the city. The EOC will provide the logistical support and site-level command for the other units included in the post-earthquake activities. A field hospital, for example, is planned to be set up near the western border of the area to provide the required medical services in the case that the main hospital is damaged. A heliport is considered near the field hospital. Some important buildings (mostly the schools and some buildings with cultural use that are expected to survive

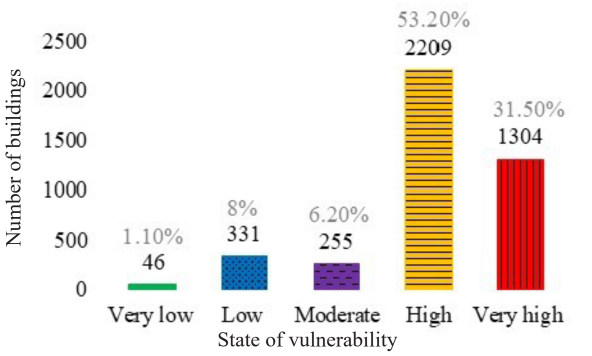


Fig. 21 Distribution of the 10 Mercalli vulnerability levels

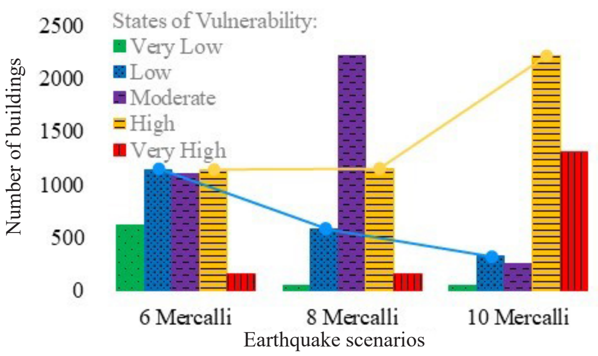


Fig. 22 Distribution of the vulnerability levels in the probable earthquake scenarios

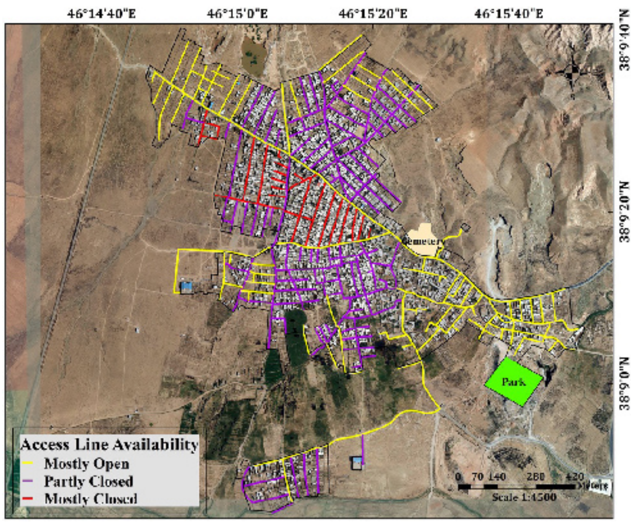


Fig. 23 Post-earthquake access line availability

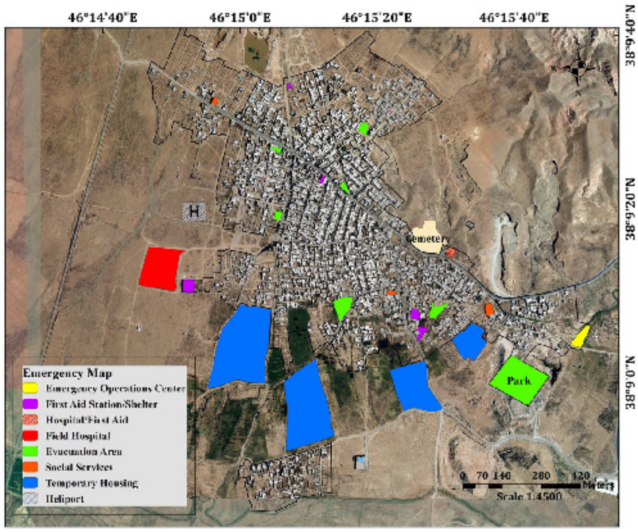


Fig. 24 Emergency map of the crisis management plan

earthquakes) are considered to be used as first aid stations and/or shelters. The main hospital, if damaged, is considered to additionally be used to assist the other first aid stations. Three different buildings in three different locations of the area studied are also considered to provide the required post-earthquake psychological counseling and the other social services. Four separate sites located in the agricultural lands near the area, moreover, are considered for temporary housing.

6 Conclusions

In the research study presented in this paper, seismic vulnerability assessment (SVA) was investigated with emphasis on its capability of being used for evaluation of resilience against earthquakes and crisis management planning. A review of relevant literature was first presented to provide background information about the related work previously carried out by the others. The review showed that SVA is well accepted to be useful in engineering studies toward effective protection against earthquakes and that it can also be used for post-earthquake planning. The main goal and motivation for this research was subsequently presented, along with the most favorable software and the methodology to perform the research. Data preparation was then discussed, and the description of the method of the research and the identification of the area selected for the case study were presented. The SVA executed was subsequently discussed and the vulnerabilities were assessed for possible earthquake scenarios. As the results of this research study demonstrated, the vulnerabilities assessed can be translated into resilience measures, and in the case of an unacceptable resistance, they can additionally be used for crisis management planning. The emergency map provided is an example of the benefits of the proposed crisis management planning through SVA that improves the resilience to earthquakes. Comparison between the location proposed for the field hospital and the location of the main hospital available in the area studied with regard to the distance from the fault and the access lines, for example, indicates the improvement mentioned. Reducing damage based on appropriate anti-seismic retrofitting attempts, reducing rehabilitation costs due to the reduced damage, and enhancing post-earthquake recovery by being prepared against earthquakes, are the other benefits with broader impacts on society that can be suggested for further investigations in future studies.

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