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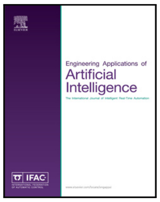

An improved hierarchical fuzzy TOPSIS approach to identify endangered earthquake-induced buildings

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ABSTRACT

As societies increase their preparedness level for facing earthquakes, many unfortunate consequences of the events may significantly decrease. An example of this can be seen in cases where pre-earthquake mitigation activities taken like identifying and renovating vulnerable buildings, assessing road network vulnerability, locating the emergency centers and identifying hazardous materials warehousing. For mitigation decision making, the seismic risk for an individual building consists of the actual dangers of the building and the risk of damage to the building from surrounding environment in time of earthquake occurrence which this concept is considered as a building exposure rate to seismic hazards. Thus, the exploration of an index by using expert knowledge for quantifying the multi-dimensional concept of building exposure rate to seismic hazards before the incidence of earthquakes is vital. According to existence of imprecision and uncertainty in experts' opinions, this paper adopts the improved hierarchical fuzzy TOPSIS approach as a fuzzy multi criteria decision making technique (FMCDM) for integrating factors affecting building exposure rate in two scenarios (daytime and nighttime). This approach effectively considers the experts' expressions and the layered hierarchy of criteria. The obtained map was categorized into 4 classes including low, medium, high, and very high risk in one of the most vulnerable regions of Tehran. Then, the robustness of the approach is verified with a sensitivity analysis; 16 experiments are conducted for two scenarios which indicate partial changes in building exposure rate.

1. Introduction

Iran is considered amongst regions prone to earthquake (Bahadori et al., 2017; Zafarani et al., 2009) in which wrecking earthquakes frequently occur with high economic losses and mortality rate (Aghamohammadi et al., 2013; Ghodrati Amiri et al., 2003; Ibrion et al., 2015; Moradi et al., 2015; Ranjbar et al., 2017); casualties reaching more than 180 thousand individuals during the past 5 decades (Omidvar et al., 2012). Construction using inferior material, building cities in proximity to faults, overpopulation, dense urban texture (Bahadori et al., 2017; Feng et al., 2013; Ghajari et al., 2017; Hashemi and Alesheikh, 2011; Park et al., 2016; Tang et al., 2017), and lack of programs for different phases of disaster management for earthquakes (Ashtari Jafari, 2010) are amongst main factors affecting vulnerability of urban societies (Chini et al., 2009; Duzgun et al., 2011). Disaster management consists of 4 phases including mitigation, preparedness, response and reconstruction. Mitigation phase involves activities to decrease economic and social risks of earthquakes, for instance, risk assessment methods to strengthen buildings and infrastructures (Aghamohammadi et al., 2013; Ghajari et al., 2017; Park et al., 2016; Saeidian et al., 2016; Tantala et al., 2008). The output of this phase is one of the essential requirements for response phase of disaster management in order to facilitate search and rescue procedures after occurrence of earthquake and plays a major role in preparedness phase of disaster management as a means for resources allocation (Ranjbar et al., 2014a, b, 2015). Previous studies regarding presentation and implementation of mitigation methods prior to earthquake occurrence can be mostly divided into two categories of vulnerability assessments and casualty estimation.

One method for improving preparedness level in time of disaster occurrence is to estimate vulnerability of buildings in study areas in order to promote situational awareness (Cockburn and Tesfamariam, 2012; Ghajari et al., 2017; Peng, 2015). Quantifying structural vulnerability is essentially challenging due to differences in mechanisms of damage for different structures (Coburn and Spence, 2006). Three main approaches have been proposed for evaluating building vulnerability including approaches based on observed vulnerability, predicted vulnerability, and multi criteria decision making (MCDM). The observed vulnerability approach makes use of fragility curves, damage probability matrices (DPM), and vulnerability functions produced from statistical analysis

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of data from previously observed earthquake damages (Barbat et al., 2010; Duzgun et al., 2011; JICA, 2000; Kappos, 2016; Karimzadeh et al., 2014; Omidvar et al., 2012). The quality of this approach is significantly dependent on the volume of collected statistical data; implementation of this approach is only possible for regions with high number of earthquake occurrence and large archives of previous earthquake data (Barbat et al., 2010; Omidvar et al., 2012). On the other hand, the predicted vulnerability approach tries to evaluate expected performance of buildings under simulated earthquake conditions designed using software such as HAZUS, SELENA, EPEDAT, INLET, SES 2002, Quake Loss, etc. (Molina et al., 2010; Ploeger et al., 2010; Remo and Pinter, 2012; Schmidtlein et al., 2011; Tantala et al., 2008). Although the predicted method has advantages such as low statistical error, the MCDM approach allows the evaluation of vulnerability with respect to experts' opinions for different scenarios (Moradi et al., 2015). In order to better control parameters and results of vulnerability evaluations, numerous researches proposed to make use of the MCDM approach (Bahadori et al., 2017; Moradi et al., 2015; Peng, 2015; Samadi Alinia and Delavar, 2011). Due to variety in choice of model, system understanding, and weights assigned to different criteria and data, the MCDM approach faces many uncertainties. Thus, it is necessary to apply methods of controlling uncertainty (Feizizadeh and Kienberger, 2017).

Protection plans against earthquakes are only advantageous when they include evaluation procedures for assessing number of injured and death toll resulting from earthquakes (Aghamohammadi et al., 2013). Estimating civilian casualties is essentially a hard process due to variety and lack of documents related to previous casualties caused by earthquakes (Coburn and Spence, 2006). Three main approaches exist for estimating civilian casualties known as empirical, analytical, and remote-sensing based approaches. In the empirical approach, casualties are estimated by investigating the relationships between earthquake parameters and number of casualties from previous earthquakes (Feng et al., 2013; Ranjbar et al., 2017; So and Spence, 2013). However, the accuracy of this approach in estimating casualties is not as satisfactory as one might desire due to the fact that seismic characteristics have no direct effect on number of casualties (Feng et al., 2013; Ranjbar et al., 2017). Analysis of casualties and losses resulting from earthquakes highlight the issue that many mortalities or series injuries amongst individuals trapped under rubble are due to destruction of buildings, and secondary disasters of earthquakes, however, destruction of buildings is commonly known as the most contributing factor (Corbane et al., 2016; Marano et al., 2010; Ranjbar et al., 2017; Wang et al., 2009; Wei et al., 2017). Therefore in the analytical approach, researches apply relationships between collapse rate of buildings and number of casualties from earthquake in order to estimate number of casualties (Feng et al., 2013; Ranjbar et al., 2017; So, 2009). The time-consuming process of gathering necessary data for this approach has limited prompt estimation of casualties from earthquakes (Feng et al., 2013). In order to speed up the process synthetic aperture radar (SAR) and optical remote sensing are used in the remote sensing approach for gathering required data regarding casualties (Feng et al., 2013; Ranjbar et al., 2017). The need for numerous pre-processing procedures on input data and high volume of processing required for detecting damages to buildings are amongst limitations of this approach.

Previous studies on mitigation plans for facing earthquakes are not capable of fully modeling building exposure rate to seismic hazards individually and comparing the results with those of surrounding buildings. This analysis requires consideration and implementation of numerous parameters in different geographical conditions. In other words, measuring the building exposure rate to seismic hazards involves computing building's actual dangers and also risk of taking damage from other features; this exposure rate leads to identifying endangered buildings prior to earthquake occurrence. For this reason many researchers have integrated the MCDM approach in GIS environment as an effective tool for spatial decision making processes (Feizizadeh and Blaschke, 2012; Feizizadeh and Kienberger, 2017). Hassanzadeh and Nedovic-Budic (2015) proceeded to identify effective criteria, relative significance of criteria and sub-criteria using AHP method and integration of criteria based on MCDM analysis in order to present an appropriate mitigation-response plan for facing earthquakes. Inability of this method for modeling effects of earthquake on individual buildings was amongst the limitations of the proposed approach. In this regard, Ranjbar et al. (2018a) presented a spatial index based on Fuzzy AHP analysis in GIS environment. This method classified damaged buildings into 5 different prioritization degrees through analysis of input raster layers. In a different study, Ranjbar et al. (2018b) proposed a rule based method for prioritizing damaged buildings from a vector-oriented database of the study area in order to decrease volume of unnecessary processing. Implementation of both methods mentioned above is highly dependent on the existence of remote sensing data from the study area, such that lack of appropriate data would lead to operational failure. Thus, it is undeniably essential to develop a method for modeling numerous parameters affecting the process of individually estimating exposure rate of each building to seismic hazards which is not operationally limited in the case where predefined images and data are not available. In this regard, the present study proposes to use an improved hierarchical fuzzy TOPSIS as a fuzzy multi criteria decision making technique (FMCDM) in GIS environment to develop a framework for detecting buildings prone to hazards. The proposed approach selects a set of criteria affecting endangered building detection prior to earthquakes in accordance with experts' opinions and then sets a weight for each criterion based on its significance. In the proposed approach, the uncertainty of expert's expressions and criteria weight is handled by integrating fuzzy set theory. Each building is then given an overall rank based on the relative significance of criteria and buildings are categorized into 4 classes based on their risk exposures including low, medium, high, and very high risk. This method was implemented in quarter 9 of district 3 of Tehran region 12, Iran, which is the historical establishment for Tehran Bazaar. The paper is divided as follows: Section 2 describes the study area and Section 3 gives a description of methodology and materials for the proposed approach. The approach is then evaluated for the study area in Section 4 and results are presented in Section 5.

2. Characterization of the study area

Tehran is the political and economic capital of Iran surrounded by the Alborz Mountains from the north and the BiBi Shahr Banoo Mountains from the south and Sepah Mountains from the east (Yaghmaei-Sabegh and Lam, 2010), where is considered part of the Alps-Himalayan orogeny (Karami et al., 2016; Karimi et al., 2011; Zolfaghari and Peyghaleh, 2016). The most populated city of Iran with a dense population reaching over 12 million (Ashtari Jafari, 2010) is considered as one of the most dangerous places on earth at risk of earthquake due to vulnerability of buildings and roads, inappropriate and non-standard construction, geographical location and also existence of numerous active faults around it (Ghodrati Amiri et al., 2003; Sarvar et al., 2011; Yazdani and Kowsari, 2017). According to most seismologists, lack of high impact seismic activities for over 187 years makes occurrence of a devastating earthquake probable in this region (Hashemi and Alesheikh, 2011; Karami et al., 2016; Omidvar et al., 2011; Yaghmaei-Sabegh and Lam, 2010).

Tehran is comprised of 22 regions (Hashemi and Alesheikh, 2011) amongst which the 12th region is one of the oldest regions of the city located at the center of Tehran with 6 districts and 13 quarters (Karami et al., 2016). Region 12 is the main economic hub of Tehran where most economic and commercial activities take place due to the existence of the traditional Bazaar area. Another feature of this region is the aggregation of most effete and historical urban texture along with the existence of numerous ministries and offices. This has led to the increase of population in this region to one million during the daytime whereas; the residing population of the region is only 241,831 individuals. It is evident that a disaster such as an earthquake would have devastating