



Determination of earthquake-risky areas in Yalova City Center (Marmara region, Turkey) using GIS-based multicriteria decision-making techniques (analytical hierarchy process and technique for order preference by similarity to ideal solution)

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Abstract

Disaster mitigation as a pre-disaster measure within the scope of disaster risk management is significant in the sense of reducing the adverse effects of earthquakes in the context of earthquake-sensitive risk planning. In the urban planning context, the existence of numerous decision makers and alternatives, which are depending on many criteria, makes decision-making process difficult. This difficulty was overcome through geographical information systems (GIS). In the context of GIS-based multicriteria decision-making (MCDM) analysis, we used analytic hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS) to determine earthquake-risky areas in Yalova City Center. First, AHP analysis related to geological and superstructure/infrastructure criteria was conducted and two separate AHP maps were obtained. Then, we conducted TOPSIS analysis to consider both criteria in the sense of earthquake risk-sensitive planning. Then, overall earthquake risk map obtained which could be used as an input for disaster mitigation processes.

Keywords Earthquake-based urban planning · GIS-based MCDM · Marmara region · Disaster mitigation

1 Introduction

As locating in one of the most seismically active regions in the World (Tan et al. 2008), Turkey has witnessed a great number of earthquakes (Ambraseys and Jackson 2000; Gurbuz et al. 2000; Erdik et al. 2004). Marmara Earthquake in 1999 is one of the significant

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earthquakes in the near past which has caused adverse outcomes affecting country's social, environmental, economic and physical systems. The consequences of Marmara Earthquake were destructive, especially considering the fact that Marmara region as the industrial center of the country and the territory surrounded by the region was responsible for one-third of Turkey's overall output at that time (Bibbee 2000). Therefore, it could be stated that the outcome of the earthquake was not solely limited to mortality but the interruption of the systems, consisting of socioeconomic mechanisms which directly affect the well-being of the country.

A large earthquake as 1999 Marmara is expected to occur along the North Anatolian Fault, expanding over 1000 km across Turkey (Aochi and Ulrich 2015). To reduce various kinds of risks arising from earthquakes, necessary measures should be taken. Leading measure in this context is to give importance to disaster management process. Disasters such as earthquakes interrupt the functioning of the society by means of threatening lives and destroying physical elements of the settlements, such as infrastructure and houses (Mansourian et al. 2006). The concept of disaster management is significant in the sense that successful implementation of the process ensures the persistence of various urban systems, including physical, socioeconomic and environmental ones. A paradigm shift is required for disaster management, by shifting from response-based approach to disaster mitigation and risk reduction approaches (Henstra and McBean 2005). By taking necessary pre-disaster measures, including disaster mitigation and risk reduction actions, undesirable consequences of disasters could be ignored or minimized.

Hence, this study aims to support one of the pre-disaster activities, providing inputs for disaster mitigation process, which are composed of pre-disaster activities. Mentioned pre-disaster activity here is the determination of risky areas, and it is significant in the context of earthquake risk-sensitive planning, which constitutes the basis of pre-disaster activities. Accordingly, the primary problem which starts the study is the fact that cities are defined as risk pools. Including components as infrastructural, superstructural, socioeconomic and demographic systems, the city is considered as a whole and it is important for cities to cope up with the probable hazards to maintain their systems' continuity.

Pre-disaster activities, including mitigation, have a special place in decreasing vulnerability of the systems which ensure the continuity of urban vitality. It is stated that the degree of disaster risk depends on the relation between hazards and vulnerable conditions, which might affect the components of urban systems (Niekerk et al. 2014). The vulnerability concept is important in that sense it is characterized by probable losses, which have either spatial or non-spatial aspects (Weichselgartner 2001). In other words; structural, social, economic or environmental losses might be actualized by a probable disaster are related to the vulnerability level of these domains, which have higher vulnerability level that is more prone to the adverse effects of disasters. Accordingly, the concept of reducing the vulnerability level has been increasing in importance and it has a direct relation with increasing capacity to cope with the adverse effects of disasters. The concept of capacity here represents "the ability to cope" which is connected to the concept of resilience, defining as the ability of a community to bounce back and recover its physical, socioeconomic and demographic systems (Paton and Johnston 2001).

Correspondingly, the action items related to reducing risks in the context of pre-disaster activities constitute a significant part of reducing vulnerability level of the urban systems and are sustained by the activities taken in the context of pre-disaster stage of the disaster management. Disaster management is consisted of five main phases as prediction, warning, emergency relief, rehabilitation and reconstruction (Moe and Pathranarakul 2006), and these phases could be divided to three as mitigation and preparedness,

response and recovery (as cited in Moe and Pathranarakul 2006). Mitigation and preparedness are involved in the pre-disaster period of disaster management, while rehabilitation and reconstruction are involved in the post-disaster period of disaster management. Both phases of disaster management, as pre-disaster and post-disaster periods, are significant in the sense of reducing risks. However, the phase which has a crucial importance in reducing risks is highly related to the pre-disaster actions. Concordantly, mitigation activities in the pre-disaster phase of the disaster management, including hazard and vulnerability analyses as well as the other required techniques as pre-zoning methods, land-use planning, community education and building codes and regulations, are necessary for the community development process (McEntire et al. 2002). Determination of risky areas in the context of earthquake-sensitive risk planning constitutes one of the actions should be taken in the pre-disaster phase of the disaster management process, which is related to the reduction of risks. It is called as mitigation, and this study aims to provide input to the mitigation process, by determining areas with earthquake risks.

In this context, there are several studies related to the determination of risky areas in the related risk management literature, which use GIS-based MCDM techniques. For instance, Moradi et al. (2015) produced an earthquake physical vulnerability map by using the ordered weighted averaging (OWA) operator. The results, then, are compared with the granular computing and intuitionistic fuzzy models. Erden and Karaman (2012) examined the weight of common parameters that have an influence on the effects of earthquakes. In this context, AHP is used for factor weighting. A hierarchical structure of the model for the simulation of an earthquake hazard map is generated. Peng (2015) integrated the results of different MCDM methods to provide regional earthquake vulnerability assessment. The key idea of this approach is to determine the most trustable MCDM methods, using the Spearman's ranking correlation coefficients. Fernández and Lutz (2010) aimed to develop a GIS-based urban flood hazard zoning of the two cities, by applying MCDM analysis (AHP), and evaluated it by means of uncertainty and sensitivity analysis. Vadrevu et al. (2010) used fuzzy set theory, integrated with decision-making algorithm in a GIS framework to map forest fire risk. Jozi et al. (2015) identified risk generated factors, by using Delphi Questionnaire; then, those criteria were prioritized by using AHP and then by TOPSIS. Zhang et al. (2014) used population information as the evaluation criterion, and a fuzzy MCDM approach was used to support a vulnerability analysis for disaster management. Then, a kernel density map was produced as a result that showed the vulnerable spatial locations. Ouma and Tateishi (2014) aimed to prepare flood mapping and estimated flood risks in growing urban areas, by using an integrated approach of AHP and GIS. Nekhay et al. (2009) aimed to produce soil erosion risk map by combining objective information, such as sampling or experimental data with subjective information, such as experts' opinions. They called this approach as analytic network process methods. Chen et al. (2015) aimed to develop a spatial MCDM prototype for the evaluation of flooding risk at a regional scale. Determined spatial indices were weighted using AHP and integrated in an AHP-based suitability assessment model under the spatial risk evaluation framework.

In addition to those studies, in this study, GIS-based MCDM analyses were implemented to determine the risky areas within the scope of earthquake risk-sensitive planning. The study area is Yalova Province in Turkey located on Marmara region, which is one of the provinces experienced 1999 Marmara Earthquake. GIS-based MCDM analyses were carried out to determine the risky areas to support pre-disaster activities. In this context, AHP and TOPSIS were used as MCDM analyses. The usage of GIS-based MCDM analyses is significant for decision-making problems, including urban planning activities consisting of a large number of criteria required for the evaluation of alternatives.

For the following section, the theory and application of GIS-based MCDM in the context of earthquake risk-sensitive planning will be explained.

2 Materials and methods

The usage of GIS in the decision-making processes of various disciplines, which are dealing with numerous decision makers and evaluation criteria, could be considered as facilitative, since it enables easy data storage, analysis and visualization. Comparably, query, mapping and spatial modeling features included in the context of GIS enable decision makers to display spatial analyses at different scales, preprocessing and data input for various spatial and statistical analyses (Jankowski 1995). Thereby, attempts which combine MCDM analyses with the favorable GIS capabilities are increasing (Chen et al. 2010).

One of the MCDM analyses is AHP, developed by Saaty, a general theory of measurement (Saaty 1987). AHP is widely used in numerous fields as well as urban planning, architecture and landscape architecture in the spatial context. Malczewski (1999) states that the main logic of AHP is divided into three as decomposition, comparative judgment and synthesis of priorities. The decomposition principle of AHP necessitates that the main problem which starts the decision-making process should be dissolved into a hierarchy; then, the comparative judgment principle requires to make pairwise comparisons of the evaluation criteria included in a hierarchical structure, and the principle of synthesis enables the construction of a priorities set for the alternatives in the context of certain hierarchy, considering their ratio scale local priorities of each (Malczewski 1999). In brief, the main functioning of AHP is to create a hierarchical structure which includes goal at the top of the hierarchy, then criteria and then decision alternatives at the bottom (Pohekar and Ramachandran 2004; Saaty 1990). After formation of criteria, the comparison of each is significant in the sense constituting the most important part of AHP, known as pairwise comparison. Saaty (1988) claims that 1 to 9 scale is used in the context of pairwise comparison. The number of 1 refers to two criteria that have equal importance, while number of 9 refers to one criterion that has an extreme importance over another (Saaty 1988).

In this study, maps including earthquake-risky areas created as consequences of AHP analyses are used as inputs in TOPSIS. TOPSIS is located in ideal point methods among various MCDM analyses. According to TOPSIS, the alternative which is closest to the ideal point is the best alternative for solution (Hwang and Yoon 1981; Kaur et al. 2009). In other words, alternative proposed by the decision makers as the best is closest to the positive ideal point, while it is farthest to the negative ideal point.

So, applied methodology could be divided into four parts as data preparation, performing AHP analyses, performing TOPSIS analysis and results and discussions.

2.1 Data preparation

Two types of data set were identified for Yalova Province, where it is located on first-degree earthquake zone and witnessed a significant earthquake in 1999. The study area has four neighborhoods as illustrated in Fig. 1.

First data set includes geological criteria, while the second contains superstructure/infrastructure criteria as indicated in Table 1.

The entire criteria related to geological characteristics of the study area were collected from Yalova Municipality on the scale of 1:5000. In the context of superstructure/



Fig. 1 The study area including its four neighborhoods

Table 1 List of criteria and sub-criteria

Criteria and sub-criteria (data sets)	
Geological criteria	Superstructure/infrastructure criteria
Sub-criteria	Sub-criteria
Geology	Impact area of health facilities
QDP filling	0–100 m
QDK filling	100–200 m
QDP	200–300 m
Kılıç formation	300 m <
Lithology	Impact area of roads
Soil	First category
Clay soil	Second category
Clay silt	Third category
Liquefaction	Quality of buildings
First degree	High quality
Second degree	Moderate quality
Third degree	Low quality
Fourth degree	Contiguous situation of buildings
	Detached
	Attached
	Floor number of buildings
	1–3 floors
	4–6 floors
	7–9 floors

infrastructure criteria, impact area of the health facilities and roads was digitized and adapted from master plan on the scale of 1:1000. The remaining criteria in the context of superstructure/infrastructure criteria, named as quality of buildings, contiguous situation of buildings and floor number of buildings, were digitized by doing field survey in the study area. The detailed information related to these criteria is explained in the following section.

2.2 Performing AHP analysis

Before explaining the applied method, it would be useful to understand the process as a whole. The overall process in applied method is indicated in Fig. 2. Therefore, the

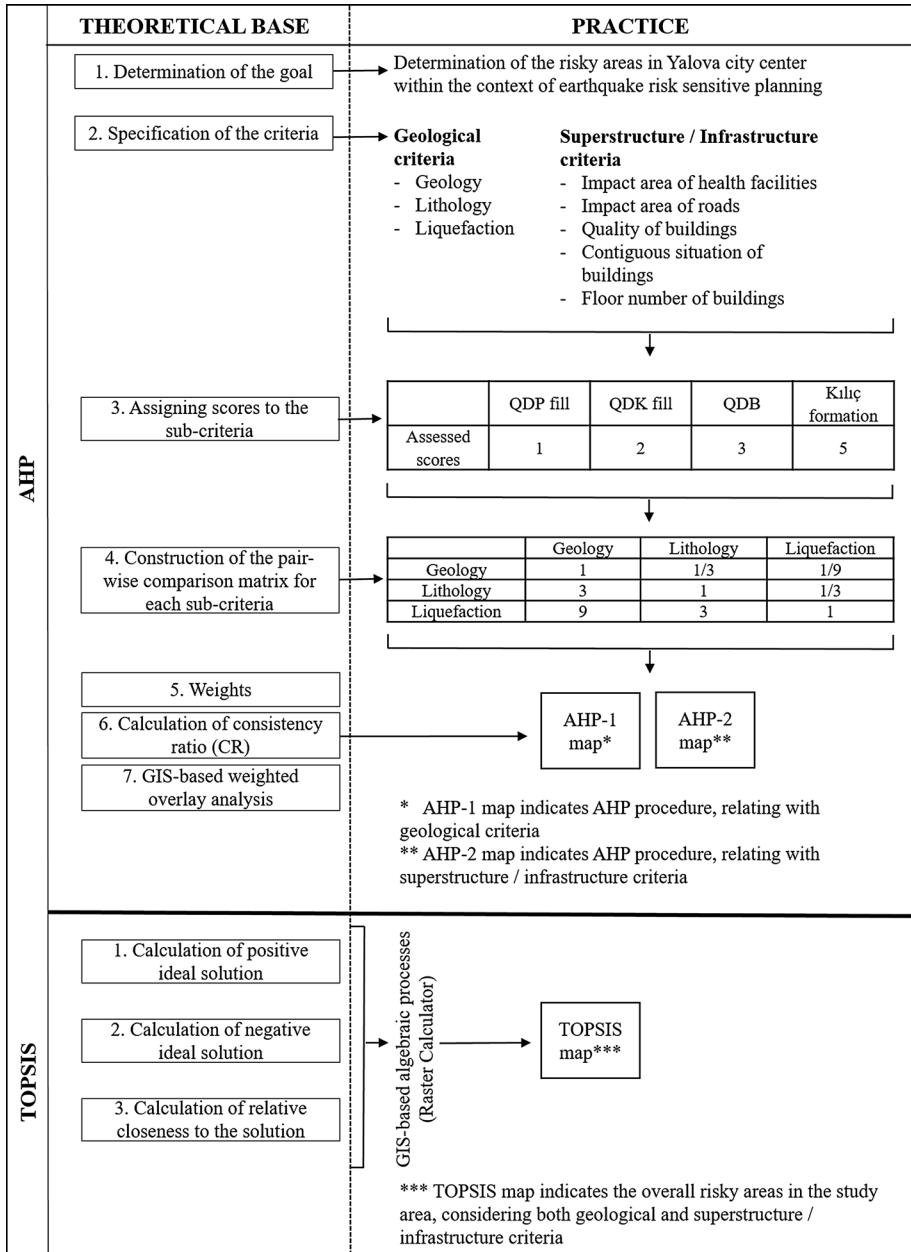


Fig. 2 The overall process in applied method

first step includes setting the goal, as determination of the risky areas in Yalova City Center within the context of earthquake risk-sensitive planning. The following steps include specification of the criteria and assigning scores to the sub-criteria, which will be explained in this section.

Since the characteristics of each sub-criterion are different, the first step of AHP requires that sub-criteria are converted to units which are comparable with each other. While doing this, decision makers (here are academicians and professionals related to geology and urban planning disciplines) sort sub-criteria based on their own value judgments. The most important sub-criterion was assigned to 5, while the least important one was assigned to 1.

2.2.1 Geological criteria maps and scoring process

2.2.1.1 Geology criteria The study area is consisted of alluvial ground to a large extent. Explanations of geological units covering the study area are described as below:

QDP fill: Beach sediment, well-washed gravel, sand, silt

QDK fill: Marine coastal plain sediment, sand, silt, clay

QDB: Marine marsh sediment, clay and organic mud

Kılıç formation: Yellow, brownish-gray, locally dark blue, laminated, medium dense clay stone, silt stone, band-shaped sand stone and mud stone. Scores assigned for sub-criteria of geology are illustrated in Table 2, located at the end of the section.

2.2.1.2 Lithology criteria The study area is consisted of three lithological units as sand, clay sand and clay silt. Lithology criteria provide general information about ground, whether it is soft or hard. It is stated that local geological characteristics have a significant role in changing seismic waves (Borcherdt 1970). Alluvial ground examples are considered as soft ground strengthens the intensity of earthquakes. Similarly, natural or artificial fill is also responsible for the increase in earthquake intensity. Since the study area is located nearby the sea shore, the ground has broadly alluvial characteristics. Besides, fill areas increase the earthquake intensity.

In the score assessing stage, sand sub-criterion was assigned to 1. Although sand has the ability of high carrying capacity, the study area is located on the sea shore and groundwater level is high. Therefore, it could be asserted that this situation could increase the probability of liquefaction, which increases the adverse effects of earthquakes. So, scores assigned for sub-criteria of lithology are illustrated in Table 2.

2.2.1.3 Liquefaction criteria Liquefaction is not observed on all kinds of ground. Liquefaction is observed on sand and clay grounds, which especially consist of young sediments and low groundwater level. It is stated that if any earthquake happens, liquefaction of soft ground with saturated cohesionless soil is responsible for adverse outcomes, considering urban physical structures (Mhaske and Choudhury 2010).

The liquefaction map of the study area has four classifications as first, second, third and fourth degree of liquefaction areas. The area having first degree of liquefaction has the highest liquefaction value, while the area having fourth degree of liquefaction has the lowest liquefaction value. Hence, scores assigned for sub-criteria of liquefaction are illustrated in Table 2.

Table 2 Scores assigned for each sub-criterion

Geological criteria				
Geology				
QDP fill	QDK fill	QDB	Kılıç formation	
1	2	3	5	
Lithology				
Sand	Clay sand	Clay silt		
1	3	5		
Liquefaction				
First degree	Second degree	Third degree	Fourth degree	
1	2	3	5	
Infrastructure/superstructure criteria				
Impact area of health facilities				
0 m–100 m	100–200 m	200–300 m	< 300 m	
5	3	2	1	
Impact area of roads				
First category	Second category	Third category		
5	3	1		
Quality of buildings				
High quality	Moderate quality	Low quality		
5	3	1		
Contiguous situation of buildings				
Detached	Attached			
5	1			
Floor number of buildings				
1 to 3 stories	4 to 6 stories	7 to 9 stories		
5	3	1		

2.2.2 Infrastructure/superstructure criteria maps and scoring process

2.2.2.1 Impact area of health facilities criteria It is significant for disaster victims to access health facilities as soon as possible in the case of probable disaster happening. Therefore, risks related to human health will be able to reduce.

Thereby, proximity of residents to health facilities plays a critical role to decrease health risks arisen from probable disasters. Accordingly, impact area of health facilities was determined considering the proximity level of residential areas in the study area. The maximum distance was specified as 300 m; it could be considered as average walking distance in a neighborhood, which is not located on sloping land. 300-m maximum distance was maintained at the lowest level and not increased to farther distances because in the case of emergency, there might not possible to find a vehicle to carry victims. Attendantly, 300-m walking distance is divided into three considering the accessibility levels as 0–100 m, 100–200 m, 200–300 m and more than 300 m. Close quarters to the health facilities were assigned to highest score, namely 5. Scores assigned for sub-criteria of impact area of health facilities are illustrated in Table 2.

2.2.2.2 Impact area of roads criteria Similar with the accessibility concern of the previous criteria, it is significant to be close to the main arterial roads if any probable disaster hap-

pening. Residential areas near to the main arterial roads are advantageous in the sense of evacuation of disaster victims and situations requiring emergency action.

Therefore, impact area of roads was determined considering the proximity of residential areas to the main arterial roads by professionals from urban planning disciplines. In this context, first category represents residential areas close to the main arterial roads, while third category represents residential areas away from the main arterial roads. Scores assigned for sub-criteria of impact area of roads are illustrated in Table 2.

2.2.2.3 Quality of buildings criteria According to the performed field survey in the study area, quality situation of buildings was classified into three as high, moderate and low qualities. While doing this, soft story, short column, age of buildings, oriel, recessed balcony, unlicensed construction and ribbon window consist of the benchmarks of this classification. Existence of all of these benchmarks increases the risk of undesired outcomes of probable earthquakes. Therefore, high-quality buildings were assigned to the highest score, while low-quality buildings were assigned to the lowest score. Hence, scores assigned for sub-criteria of quality of buildings are illustrated in Table 2.

2.2.2.4 Contiguous situation of buildings Locating in contiguous situation increases the probability of earthquakes' adverse effects. Since buildings which have different story heights show different oscillation periods and this situation causes the crash of buildings, critical damages might occur in the case of earthquake. Moreover, story levels which are not located in the same alignment in the context of contiguous buildings also increase the possible losses. This situation might cause the formation of seismic pounding effect in the case of earthquake. Seismic pounding effect might cause different contiguous buildings to make different translatory motions. Therefore, contiguous buildings cannot separate enough from themselves and story of a building might collapse with the column of another building and this situation might cause wreckages (Balyemez and Berköz 2005). Therefore, scores assigned for sub-criteria of contiguous situation of buildings are illustrated in Table 2.

2.2.2.5 Floor number of buildings There is a relation between floor number of buildings and earthquake risks. Increasing floor numbers might increase probable adverse outcomes of earthquakes, especially for the buildings which are located on poor bearing soil. Since the study area is located on first-degree seismic zone, existence of low-rise buildings is significant, considering earthquake risks. Besides, one of the most significant factors, affecting the period of a building, is its height. Increasing number of floors means increasing building period (Arnold et al. 2006). In the case high-rise buildings are located on poor bearing soil, resonance might occur due to the fact that poor bearing soil has high oscillation period. Hence, scores assigned for sub-criteria of floor number of buildings are illustrated in Table 2.

2.2.3 Implementation of AHP: geological criteria (AHP-1) and superstructure/infrastructure criteria (AHP-2)

AHP as a process is consisted of seven stages in this study: determination of the goal, specification of the criteria, assessing scores to the sub-criteria, carrying out pairwise comparison, determination of weights, calculation of consistency ratio and obtaining AHP-1 and AHP-2 risk analysis maps by entering weights in the context of GIS (see Fig. 2). The

first three stages were explained in the previous sections. In this section, the remaining stages are to be explained.

2.2.3.1 Pairwise comparison The main logic of pairwise comparison depends on the pairwise scale developed by Saaty (1988, 1990, 1994). Pairwise comparison matrix is generated based on prioritization of criteria by decision makers. In other words, each criterion is compared with each other based on decision makers’ values. While doing this, decision makers predicate on pairwise scale.

Let us assume that there are m alternatives and n attributes considered by decision makers. Then, the pairwise comparison matrix (A) could be illustrated as (Ying et al. 2007):

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}$$

In the view of such information, pairwise comparison matrix related to geological and superstructure/infrastructure criteria is composed. Considering the local conditions of the study area, prioritization of the geological criteria is determined in order of priorities as liquefaction, lithology and geology. Additionally, quality of buildings, floor number of buildings, contiguous situation of buildings, impact area of roads and impact area of health facilities are considered in order of priorities for infrastructure/superstructure criteria. Therefore, assigned scores are indicated in the pairwise comparison matrixes as, respectively (see Tables 3 and 4). Those values are assigned by a group of geological engineers and urban planners, reflecting their value judgments related to the criteria:

2.2.3.2 Weights To determine the weights of each criterion, first of all, columns of the pairwise comparison matrix (see Table 12) are used and C matrix is constituted. After C matrix is constituted, significance levels as percent are calculated. In order to calculate matrix C , formulas indicated below are used, respectively (Saaty 1980; Rao 2012):

Table 3 Pairwise comparison matrix for geological criteria

Pairwise comparison matrix for geological criteria			
	Geology	Lithology	Liquefaction
Geology	1	1/3	1/9
Lithology	3	1	1/3
Liquefaction	9	3	1

Table 4 Pairwise comparison matrix for infrastructure/superstructure criteria

Pairwise comparison matrix for infrastructure/superstructure criteria					
Impact area of health facilities	1	1/2	1/4	1/6	1/8
Impact area of roads	2	1	1/2	1/4	1/6
Contiguous situation of buildings	4	2	1	1/2	1/4
Floor number of buildings	6	4	2	1	1/2
Quality of buildings	8	6	4	2	1

$$b_{ij} = a_{ij} / \sum_{i=1}^n a_{ij} \text{ is calculated to generate matrix } B_i = \begin{bmatrix} b_{11} \\ b_{21} \\ \vdots \\ b_{n1} \end{bmatrix}$$

Indicated B_i matrix above shows the values only for B_i . Therefore, the same process should be repeated for B_i to B_n . Matrixes having single columns for B_i to B_n constitute a single matrix C by combining together. Accordingly, C matrix, which is the same number as criteria (m), is gained as:

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix}$$

The last step of getting weights process requires arithmetic mean of row values of matrix C . Therefore, matrix D , which shows the weight values, is constituted by using the formula as:

$$d_i = \sum_{j=1}^n c_{ij} / n$$

Hence, matrix D (namely, weights) is constituted as:

$$D = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix}$$

By using the above formula, the weights of each criterion are determined for geological and infrastructure/superstructure criteria, respectively, in Tables 5 and 6 as:

2.2.3.3 Calculation of consistency ratio (CR) The primary purpose of calculating CR is to control whether decision makers assign consistent scores to each criterion of the pairwise comparison matrix. The base of this calculation depends on the comparison between π and criteria. To calculate π , multiplication of values of the pairwise comparison matrix (A) and weights (D matrix) is used and matrix E is obtained as (Ying et al. 2007):

$$E = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \times \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix}$$

Table 5 Weights calculated for geological criteria

Weights for geological criteria	
	Weights
Geology	0.0769
Lithology	0.2307
Liquefaction	0.6923

Table 6 Weights calculated for infrastructure/superstructure criteria

Weights for infrastructure/superstructure criteria	
	Weights
Impact area of health facilities	0.0441
Impact area of roads	0.0759
Contiguous situation of buildings	0.1436
Floor number of buildings	0.2681
Quality of buildings	0.4684

After matrix E is gained, the following formula is used to calculate π as:

$$\pi = \sum_{i=1}^n \frac{d_i}{w_i} / n,$$

where w_i is the weight of each criterion. The last steps for calculating CR include the calculation of consistency index (CI). Then, CR is able to be calculated. In order to gain CI, the following formula is used as (Marinoni 2004):

$$CI = \pi - n / \pi - 1$$

The following step enables to calculate CR. This step is consisted of division of CI to random indicator (RI). The value of RI depends on the criteria number as indicated in Table 7 (Saaty 1994).

After finding appropriate RI value, the following formula gives the value of CR (Marinoni 2004):

$$CR = CI / RI$$

If CR value is below 0.1, then it could be stated that the pairwise comparison matrix is created by the decision makers in a consistent way. CR value for geological criteria is calculated as $CR = 0.00$, meaning the best suitable value for consistency. Furthermore, CR value for infrastructure/superstructure criteria is calculated as $CR = 0.0174$, meaning suitable for consistency since this value is below the value of 0.1. Hence, AHP-1 and AHP-2 maps indicating for geological and infrastructure/superstructure criteria, respectively, are illustrated as shown in Figs. 3 and 4 as.

As illustrated in Figs. 3 and 4, geological criteria and superstructure/infrastructure criteria are evaluated separately in the context of AHP. In the next section, these criteria are evaluated simultaneously in the context of technique for order preference by similarity to ideal solution (TOPSIS).

Table 7 RI values depending on criteria number (n)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49



Fig. 3 AHP-1 map including geological criteria. The white dotted lines indicate the high and moderate risks. Therefore, areas having lower risk are separated from the high and the moderate ones



Fig. 4 AHP-2 map including infrastructure/superstructure criteria

2.3 Performing TOPSIS analysis

In the AHP procedure, various values were assigned to each sub-criterion, which depend on various value judgments. Herewith, each criterion is assigned different weights, which depend on the assigned values, considering their importance levels. In this process, namely TOPSIS, the alternative, which is closest to the best solution (in this case pixels having higher pixel values, comparing with the others), will be determined, by applying TOPSIS as a MCDM technique. In other words, AHP is used for weighting, while TOPSIS is used for ranking at this stage.

In TOPSIS procedure, the AHP maps illustrated in Figs. 3 and 4 have been analyzed as inputs. Each of the pixels composing the AHP maps was considered as alternatives for the risky areas with different levels in TOPSIS. Therefore, it could be stated that the value which each pixel has is the fundamental input that is analyzed in the context of TOPSIS. Additionally, those pixels having the same or different values (pixels having the same value are shown as the same color) are all indicate alternatives, which are evaluated in TOPSIS procedure to determine which alternatives constitute better alternative areas. In the AHP procedure, sub-criteria of evaluation criteria constituting geological and superstructure/infrastructure criteria were assigned to scores of 1 to 5, as 5 indicating the areas having less

risk, comparing with the other areas. Therefore, in consequence of AHP, areas having less risk had pixel value of 5. In TOPSIS, the logic is the same.

As indicated earlier, for the following computation phase of TOPSIS, pixel values calculated via AHP analyses are used as alternatives. The first phase of TOPSIS calculation includes the calculation of weighted normalized values v_{ij} . In the AHP-1 and AHP-2 analyses, those values were calculated, illustrated now as pixels having certain values (see Figs. 3 and 4). Hence, remaining algebraic calculations of TOPSIS performed on the GIS environment are introduced as below (Hwang and Yoon 1981; Önüt and Soner 2008; Pazand et al. 2012):

1. Calculation of positive ideal solution (A^+)

Criteria which are closest to the ideal solution are included in the set illustrated below:

$$A^+ = \{v_1^+, v_2^+, \dots, v_i^+ = \{(\max v_{ij} | i \in I'), (\min v_{ij} | i \in I'')\}$$

where I' represents benefit, while I'' represents the reverse. The maximum value in the above set is considered as the positive ideal solution.

2. Calculation of negative ideal solution (A^-)

Criteria which are farthest to the ideal solution are included in the set illustrated below:

$$A^- = \{v_1^-, v_2^-, \dots, v_i^- = \{(\min v_{ij} | i \in I'), (\max v_{ij} | i \in I'')\}$$

where I' represents benefit, while I'' represents the reverse. The minimum value in the above set is considered as the negative ideal solution.

3. Calculation of separation from ideal solutions

Separations from positive ideal and negative ideal solutions, respectively, are calculated using the formulas as:

$$D_j^+ = \sqrt{\sum_{i=1}^n (v_{ij} - v_i^+)^2} \quad j = 1, 2, \dots, J$$

$$D_j^- = \sqrt{\sum_{i=1}^n (v_{ij} - v_i^-)^2} \quad j = 1, 2, \dots, J$$

4. Calculation of relative closeness to the ideal solution

The main goal of this stage of TOPSIS is to calculate the ratio of negative ideal separation in the overall separation. Therefore, the following formula is used to calculate relative closeness to the ideal solution as:

$$CC_j^+ = D_j^- / (D_j^+ + D_j^-) \quad j = 1, 2, \dots, J$$

According to this equation, related alternative is more preferable, while C_i^+ approaches to 1. On the other hand, related alternative approaches to the negative ideal solution, while C_i^+ approaches to 0.

All of the calculation procedures of TOPSIS explained above is illustrated within the context of a hypothetical example, illustrated in Fig. 5. Let us assume that there is a 2×2 pixel map. Each pixel represents a single alternative, and the evaluation criteria for those

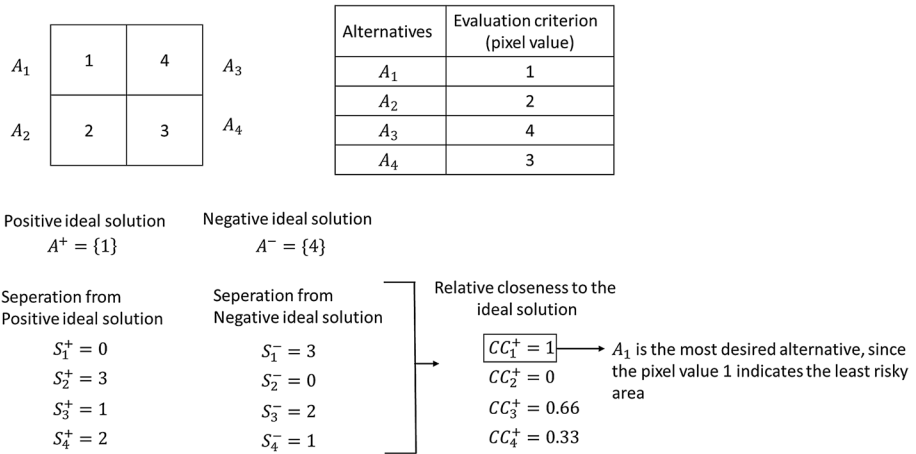


Fig. 5 A hypothetical example of TOPSIS

alternatives (namely, pixels) are their pixel values. Depending on this information, an alternative, which has the minimum pixel value, has the greatest earthquake risk level in this case (since the risk level decreases from 1 to 5). The remaining calculation procedure was explained above, and all of those calculations were applied in the GIS environment, by using its algebraic functions.

In the light of this information, algebraic expressions of TOPSIS explained above are calculated in the context of GIS and the final map which shows earthquake risks considering geological and infrastructure/superstructure criteria jointly is produced as shown in Fig. 6.

Application of MCDM in spatial decision-making process has certain advantages that it allows to consider a great number of criteria by the decision makers. Decision makers specify criteria and each criterion under the specified criteria. Then, each criterion is assigned to scores (scale of 1–5, 1–10, 1–100, etc.) depending on value judgments of decision makers. Therefore, each criterion is standardized and could be compared with each other. Similarly, criteria are assigned to scores by decision makers depending on their value



Fig. 6 TOPSIS map including both geological and superstructure/infrastructure criteria

judgments and pairwise scale, developed by Saaty, and as the last step, weights of criteria are gained. It is one of GIS's advantages that the obtained weights in MCDM process are possible to visualize with it. By conducting algebraic expressions of AHP in GIS, AHP-1 and AHP-2 maps are produced.

3 Results and discussion

Dissociation of AHP-1, AHP-2 and TOPSIS analyses' results will be more explanatory in the sense considering geological criteria, infrastructure/superstructure criteria and the combination of both. AHP-1 analysis in the context of geological criteria (Fig. 2) indicates that the highly risky areas are mostly the places having higher liquefaction potential. This is due to the fact that liquefaction criterion has the highest value in the pairwise comparison matrix considering the earthquake risks related to geological criteria in the study area.

AHP-2 analysis in the context of infrastructure/superstructure criteria (Fig. 3) shows that especially areas having high-rise and low-quality buildings have higher risks since quality and floor number of buildings have higher values in the pairwise comparison matrix considering the earthquake risks. The city center located east side of the river illustrating as red color has the highest risk in the study area due to having high-rise buildings as well as low-quality buildings, which are mostly old and having soft stories and short columns.

AHP-1 and AHP-2 analyses show earthquake risks in the context of geological and infrastructure/superstructure criteria in a separate way, respectively. Carrying out TOPSIS analysis enables to combine these two criteria; consequently, an overall risk map is produced, involving both criteria (Fig. 4). While conducting TOPSIS analysis, AHP-1 and AHP-2 analyses maps are compounded in a way that both criteria are assigned to equal importance. The overall risk map indicates that the city center, located on east side of the river, has the highest earthquake risk due to having low-quality, high-rise and attached buildings. The neighborhood, located on the west side of the river, has lower earthquake risk due to having good-quality, low-rise and detached buildings. Although having attached and average quality buildings, the south side of Fevzi Çakmak Neighborhood has low risk since it has low-rise buildings and low levels of liquefaction.

Geological and superstructural/infrastructural criteria were combined in this study to develop an earthquake risk map. Based on the main objective of the study, the variables might be diversified. For instance, in some studies, socioeconomic variables are added to the GIS-based MCDM analyses, relating to risk and sustainability assessments (see Marulanda et al. 2013 and Reza et al. 2011, respectively). However, in this study, the main objective is designated to examine the effects of geological characters of the space and artificial structures built on it. In other words, physical components of the space are evaluated in the context of GIS-based MCDM earthquake risk determination process.

As Danumah et al. (2016) and Papaioannou et al. (2015) state, using AHP as a MCDM technique may indicate some failures, since it requires various value judgments of different experts. In this context, Saaty (1980) identified a consistency ratio threshold which is below 10%, enabling a proper judgment. Although there could be a probability of occurrence of this kind of failure in this technique, by courtesy of the fact that consistency ratio enables proper judgments, AHP is one of the most used MCDM techniques in the risk determination processes (Tefamariam and Sadiq 2006; Yoshimatsu and Abe 2006; Carreño et al. 2007; Kayastha et al. 2013; Stefanidis and Stathis 2013; Yang et al. 2013; Zou et al. 2013; Siddayao et al. 2014; Taylan et al. 2014).

Besides, as applied in this study, there are various studies performed integrated AHP-TOPSIS approach (see Perçin 2009; Onder and Dag 2013; Barrios et al. 2016; Hanine et al. 2016). The main objective first using AHP is to assign the weights of the determined criteria. Then, TOPSIS is used to determine which alternative resulting from AHP analyses is better comparing with the other alternatives. In other words, TOPSIS is used to identify the better alternatives. (Remember, each pixel indicates a single alternative in this study.) This constitutes the unique part of this study that differs from the other studies indicated in the previous paragraph using AHP in the context of risk determination processes.

4 Conclusion

In this study, risky areas in the context of earthquakes are determined in the study area, Yalova City Center. Determination of risky areas is significant in the sense strengthening the pre-disaster stage of disaster management. Hereby, it is possible to take necessary measures to reduce earthquake risks after the determination of risky areas. Accordingly, GIS-based MCDM is used to determine the risks.

First of all, defined criteria as geological and infrastructure/superstructure are considered in two separate AHP analyses, AHP-1 (Fig. 2) and AHP-2 (Fig. 3), respectively. Therefore, two risk maps are produced that AHP-1 indicates risky areas considering geological criteria and AHP-2 indicates risky areas considering infrastructure/superstructure area. Then, TOPSIS analysis carried out to determine the overall earthquake risks combining the two criteria as geology and infrastructure/structure.

Then, by conducting algebraic expressions of TOPSIS, TOPSIS map which shows the overall earthquake risks is produced. Therefore, it could be true to say that the usage of GIS-based MCDM in decision making related to space and place could benefit decision makers to handle storage and preparation of data to analyses, conducting analyses and visualization of obtained results.

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