New approaches to modelling of local seismic amplification susceptibility using direct characteristics of influencing criteria: case study of Bam City, Iran

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Abstract

This paper proposes a new model in evaluating local seismic amplification susceptibility by considering direct characteristics of influencing criteria and it deals with uncertainty of modelling through production of fuzzy membership functions for each criterion. For this purpose, relevant criteria were identified by reviewing previous literature. These criteria include alluvial thickness, stiffness and strength of alluvial deposits, type of soil and particle size distribution of alluvial deposits, depth of groundwater, type of rock, topographic irregularities, slope and type of bedrock. Two methods, Analytic Hierarchy Process (AHP) and Fuzzy Logic (FL), were applied in order to define priority rank of each criterion and sub-criteria of each criterion through interview data of 10 experts. The criteria and sub-criteria were combined using Weighted Linear Combination method in GIS to develop a model for assessing local seismic amplification susceptibility in the study area of Bam city, Iran. The model's output demonstrated high to very high seismic amplification levels in central, eastern, north-eastern and northern parts of the study area. The validation results based on overall accuracy and Kappa statistics showed 73.6% accuracy, 0.74 Kappa indicating a good fit to the model's output. This model assists planners and decision makers to produce local seismic amplification susceptibility to be incorporated in designing new development plans of urban and rural areas, and to facilitate making informed decision regarding safety measures of existing buildings and infrastructures.

Keywords*: Seismic Amplification Susceptibility, Site Effects, Spatial Modelling, Analytic Hierarchy Process, Fuzzy Logic and GIS.*

1. Introduction

This paper explores direct characteristics of influencing criteria in evaluating susceptibility of local seismic amplification and deals with uncertainty of modelling through production of fuzzy membership functions of each criterion. MERM microzonation manual (2003) sets different criteria effecting the amplitude and duration of ground shaking at a specific site. These include "the magnitude of the earthquake, focal point and depth of the earthquake, directivity of the energy released, distance of rupture from the site, geological condition from the site to the location of the earthquake, local geological settings, geotechnical properties, and topographical condition of the site" (SM Working Group, 2015;Boore, 2003;Hassanzadeh et al., 2013;Castelli et al., 2016a;Castelli et al., 2016b). It has long been known that local conditions of foundation soils have a significant impact on the effects of an earthquake on building destruction level, as it was demonstrated in previous earthquakes such as Mexico City, 1985 (Beck and Hall, 1986), Kobe, 1995 (Wald, 1996), Izmit, 1999 (Tang, 2000), Umbria-Marche earthquake, 1997 (Moro et al., 2007) and Bam earthquake, 2003 (Ramazi and Jigheh, 2006) and L'Aquila earthquake, 2009 (Monaco et al., 2012;Capilleri et al., 2014) and buildings that were located on unconsolidated sediments had greater destruction levels (Ramazi and Jigheh, 2006).

The aim of seismic microzonation studies is to produce ground-shaking map that can communicate efficient data to planners and policy makers in a geographic area to make informed decision regarding development policies in urban areas. Therefore, this community requires accurate information for developing mitigation plans and strategies. In the spite of this, there are uncertainties in determining local seismic amplification at a site, as this can be influenced by complex factors such as the earthquake source (epicenter of the earthquake), wave propagation and site condition. Uncertainty in these criteria results in uncertain ground-motion estimate from earthquakes (Wang et al., 2017;Wang et al., 2016;Petersen et al., 2016). There are different methods that have been used for assessing ground-motion hazards such as Probabilistic Seismic Hazard Analysis (PSHA), Deterministic Seismic Hazard Analysis (DSHA) and Scenario-based Seismic Hazard Analysis (SSHA). Probabilistic Seismic Hazard Analysis (PSHA) method (Cornell, 1968;Atkinson et al., 2015;Petersen et al., 2016) depends on "the length of the causative faults and depth of the earthquake", which are generally unknown thus causing uncertainty in assessing ground-motion of earthquakes (Wang et al., 2017). In DSHA method (Campbell, 2003;Atkinson and Boore, 2006) lack of relevant ground-motion attenuation relationship for specific geographic areas can cause uncertainty in assessing ground motions of an earthquake (Wang et al., 2017). SSHA (Panza et al., 2012) applies ground-motion simulations of a scenario earthquake using specified source, path and site parameters, however the parameters needs to be defined in more details. By conducting many simulations, earthquake variability of different sources, ground-motion propagation characteristics, and local site effects can be considered. Therefore, uncertainties using SSHA are quantified explicitly (Wang et al., 2017), although this method is still under development. Furthermore, Aucelli et al. (2018) proposed a method for producing susceptibility index to local seismic amplification in Isernia Province, Italy based on geological and geomorphological properties of studied areas. This research mostly followed an evidence based approach to estimate susceptibility level of local seismic amplification in the area, although they have not considered the use of multi-criteria decision-making methods (MCDM)in their study. Several MCDM methods have been developed to deal with ranking and weighting of criteria, such as Regime (Hinlopen et al., 1983), ELECTRE family (Figueira et al., 2005), Analytical Hierarchy Process (AHP) (Saaty, 1980), and Multiple Attribute Utility approach (MAUT) (Keeney and Raiffa, 1993). In this research, Analytical Hierarchal Process (AHP) (Saaty, 1980) has been utilize as it is one of the most useful method in calculating criteria’s weights, and AHP in combination with GIS were applied to produce seismic microzonation map of Bangalore (Sitharam and Anbazhagan, 2008) (2008), Dehli (Mohanty et al., 2007), Haldia, Bengal Basin (India) (Mohanty and Walling, 2008), Erbaa (Turkey) (Akin et al., 2013) and Al-Madinah (Moustafa et al., 2016) and generating ground-shaking map for Catania (Italy) using GIS (Castelli et al., 2016a). According to these methods experts evaluate and choose among qualitative and quantitative criteria. Since experts’ judgments can be subjective and imprecise, uncertainty also exists in this analysis. Such uncertainties can be dealt with based on fuzzy logic principles (Zadeh, 1965) and inference systems (Klir, 2004;Zadeh, 1975).

Fuzzy Logic method was used for evaluation of earthquake damage to buildings (Sen, 2010), and evaluation of seismic microzonation (Teramo et al., 2005;Nath and Thingbaijam, 2009;Boostan et al., 2015). Although, there were a number of publications on evaluating the local seismic amplification in the literature, but few researchers have considered the use of Fuzzy Logic approach and direct characteristics of each criteria in evalaution of local seismic amplification susceptibility. These are motivations behind conducting this research.

The purpose of this paper is to develop a model for evaluation of local seismic amplification based on direct characteristics of relevant criteria. Firstly, selected criteria were weighted using AHP method by interviewing 10 experts, next criteria were converted into fuzzy sets, then fuzzy membership functions (MFs) were produced, finally WLC method and fuzzy inference rules were applied to produce a level - 1 susceptibility map of local seismic amplification for a study area.

2. Material and methods

This study investigates the importance of influencing factors on susceptibility of local seismic amplification. Firstly, these criteria have been derived by a critical analysis of previous literature. Secondly, Analytic Hierarchy Process (AHP) and Fuzzy Logic (FL) Methods have been applied to deal with weighting and fuzziness of criteria due to associated uncertainties in decision-making process on preparing susceptibility map of local seismic amplification through interviewing experts. Next, criteria and sub criteria have been combined based on WLC method to develop a model. Finally, the model has been validated using Overall Accuracy (OA) and Kappa statistics methods by comparing to the measured. This study has been conducted on the case study of Bam City, southeast of Iran (Figure 1), and it followed four steps of investigations shown in figure 2.

Figure 1. Case study of Bam City, Iran

Figure 2. The methodological approach of the study

2.1. Identification, Weighting and Fuzzification of Criteria

The susceptibility level of local seismic amplification can be influenced by several criteria. These criteria were identified by reviewing literature and interviewing experts through data gathering process. Then, identified and selected criteria were weighted and fuzzified using AHP and FL methods, as explained in the following sub-sections.

2.2.1. Analytical methods

2.2.1. Analytic Hierarchy Process (AHP) method

AHP is one of the most commonly used multi-criteria decision making (MCDM) tools, and allows the consideration of both objective and subjective factors in ranking alternatives in a hierarchical decision model (Saaty, 1980;Saaty, 1990). This method is applied to convert the experts' view on the importance of each criterion and sub-criterion to a numerical value by comparing each other, one pair at a time (pair-wise comparison) (Saaty, 1980).

AHP matrix (A) is developed from the pair-wise comparison of the relative importance of criterion A_i to criterion A_j (α_{ij}, represents a quantified judgment on a pair of criteria) (Figure 3). The values assigned to α_{ij} according to the Saaty's scale (1980) range from 1 to 9 or their reciprocals. In order to calculate the priority ranking of each criterion (weight), Saaty (1990) suggested the mathematical computation of eigenvector based on Eq. 1& 2.

Figure 3.AHP matrix (A)

$$\lambda_{max} = \sum_{j=1}^{n} a_{ij} \frac{Wj}{Wi} \qquad \textit{(Eq. 1)}$$

Where: λ_{max}= the largest eigenvalue; α_{ij}= judgment; W_i & W_j = numerical weights for judgment α_{ij}.

$$(A - \lambda_{max}\, I\,)X = 0 \qquad \textit{(Eq. 2)}$$

Where: A= AHP matrix; λ_{max}= the largest eigenvalue; I= Unique matrix; X= eigenvector.

In addition, the assignment of weights to each criterion relates to the process of the experts' logical and analytical thinking, which is tested for each matrix with Consistency Ratio (CR) statistics. If this statistics is less than 0.1 (CR < 0.1), the experts' answers are logical. Following the testing for consistency, the weights are aggregated to determine ranking of decision alternatives (the weights) for each criteria. Therefore, in this research, AHP method is applied to calculate the degree of importance of each criterion influencing on the susceptibility level of local seismic amplification in a region,

2.2.2. Fuzzy Logic (FL) method

Fuzzy logic is a method of "approximating modes of reasoning" (Novák et al., 2012), and it is a mathematical tool that deals with uncertainty in a different way that can relate independent variables to dependent variables. Zadeh (1965) introduced Fuzzy set theory indicating that the boundary is not precise and the gradual change is expressed by a membership function, and it changes from non-membership to membership in a fuzzy set (Eq. 3). The characteristic function value range between 0 and 1. Each membership function is represented by a curve that indicates the assignment of a membership degree in a fuzzy set to each value of a variable. Curves of the membership functions can be linear, triangles, trapezoids, bell-shaped, or have more complicated shapes (Figure 4) depending on the purpose of the subject (Demicco and Klir, 2003).

$$A_a = \{x \, \mathcal{E} \, X \mid \mu_A(x) \geq a\} \qquad \textit{(Eq. 3)}$$

Where A_a is called the a-cut or a-level set of A, and $\mu_A(x)$ represents membership degree of the element x.

Figure 4. Fuzzy membership functions (After Mancini, 2012)

Fuzzy systems are mainly based on expert knowledge to formalize reasoning in natural language mostly using sets of fuzzy inference rules or "*if–then*" rules (Eq. 4).

$$If \; x \; is \; A \; then \; y \; is \; B \qquad \textit{(Eq. 4)}$$

As membership functions curve can easily be changed by small increments based on expert knowledge, therefore, fuzzy logic can characterize and model geologic systems in an efficient way (Klir, 2004;Demicco and Klir, 2003). Therefore, in this research using Fuzzy set, the uncertainties in producing microzonation map of ground shaking can be managed by defining fuzzy membership functions for each criterion. This happens by assigning meaningful values (0 to 1) to each individual (sub criteria) of each criterion. For the purpose of defuzzification, largest of maximum method was applied. Based on this method the largest value of the fuzzy subset was the output value (Mancini et al., 2012).

2.3. Data gathering

In order to identify influencing criteria in local seismic amplification the required data were collected through a literature review and semi-structured interviews with 10 experts who were involved in the geology, seismology, tectonic, structural engineering, and geomorphology fields. They were asked about the criteria that can influence local seismic amplification, and then these data were analyzed using AHP and FL methods as explained in the following:

2.3.1. Determining the relevant criteria by reviewing literature

The potential criteria influencing local seismic amplification susceptibility were determined through a critical review of literature. By reviewing documents on earthquake engineering, seismology, geology, tectonic and structural engineering, geomorphology and seismic microzonation reports and guidelines (Fäh et al., 1997;Ding et al., 2004;Molina et al., 2010;Mundepi et al., 2010;Marulanda et al., 2012;Hassanzadeh et al., 2013;Federal Emergency Management Agency (FEMA), 2014;Fraume et al., 2014;Grelle et al., 2016;Grelle et al., 2014;SM Working Group, 2015;Rehman et al., 2016;Nwe and Tun, 2016;Global Earthquake Model (GEM), 2017;CAPRA, 2017;Michel et al., 2017;Trifunac, 2016;Hassanzadeh and Nedovic-Budic, 2016), and in total 14 influencing criteria were identified (Table 1).

Table 1.Relevant criteria that influence on local seismic amplification susceptibility

2.3.2. Experts' Knowledge data

a) Interviewing disaster managers (semi-structured interviews) to determine the important criteria

The most important criteria were determined by conducting a semi-structured interview with 10 experts using the snowball or chain-referral sampling method (Biernacki and Waldorf, 1981). In this study, all 10 interviewees were highly experienced and had been involved in seismic microzonation studies. The average age of the sampled individuals was 43 years, and all of them had a postgraduate degree.

A list of criteria that were identified by reviewing previous studies were given to the experts and they were requested to add other criteria if they thought they were applicable. They were asked to rank each criterion using a five-point Likert Scale (Likert, 1932), so respondents could choose the option that best reflected their opinion on each criterion. When surveying many people on the same criterion, the five codes could be summed up, averaged or calculate the mode, indicating overall positive or negative orientation towards that criterion. This was the basis from which this method was used to identify the degree of importance for each criterion in local seismic amplification in a region. Therefore, in order to elicit the most relevant criteria, the significance of specific factors were measured on a five-point Likert Scale where 1 represents ‘not important at all’, 3 ‘of little importance’, 5 ‘of average Importance’, 7 ’very important’, and 9 ‘extremely important’ (Likert, 1932;Jamieson, 2004). The collected data were analysed and criteria with mean ratings above ‘5’ (‘of average important’) were selected (Table 2). These have been then considered for further analysis using the Analytic Hierarchy Process (AHP) method.

Table 2.The average importance criteria based on 5-point Likert Scale

b) Interviewing disaster managers (structured interviews) in order to collect data for computing the relative importance (weights) of the criteria

A questionnaire based on AHP matrix (A) was developed for a pair-wise comparison of the relative importance of the criteria for calculating the weights (priority ranking) of each criterion. As AHP is a subjective method therefore a large sample size is not needed (Cheng and Li, 2002;Lam and Zhao, 1998). For this reason, data were collected by interviewing 10 experts (the same experts who were interviewed in the first round) based on the structured questionnaire (closed-ended questions). They were asked to compare the relative importance of each criterion against all others, based on Saaty's scale by verbal preferences (Saaty, 1980). A pair-wise comparison that was carried out with an expert is shown in Table 3. These data are used by the AHP method to compute the weight of each criterion as explain previously.

Table 3.The results of pair-wise comparisons of the selected criteria with each other based on the AHP matrix

c) Determining fuzzy set and fuzzification of thresholds of sub-criteria for each criterion

In the next step, since each criterion and its sub-criteria has different effect on local seismic amplification susceptibility in a region, fuzzy membership functions (MFs) for sub criteria of each criterion are defined. As, designed parameters of each membership function depends on experts knowledge, then number of memberships, the shape, the positioning, and the overlay area of memberships of each MFs for each criterion would be different. To conduct this analysis, 10 experts were interviewed regarding membership degree of sub criteria of each criterion, and mode of each sub criteria was calculated and MFs for each criterion was depicted as described in the following:

- Thickness of soil and sediments: an effective factor in site effect assessment is the thickness of sediments. Rezaei et al. (2009) stated that the soil thickness demonstrated a positive relationship to damage rate observations in the Bam earthquake. This layer was produced by 245 geophysical, geotechnical, and sedimentological sampling sites across the city. The alluvial thickness varies in different parts of the city. In the northern part of the city, the sediment (marine to continental Quaternary deposits including alluvial plain gravels with interlayered clay, silt and sand) thickness ranges from 0 m, where bedrock is exposed beneath Arg-e-Bam, to 90 m across most of the northern half of the study area. Toward the south and center of the study area, sediment thickness increases over a short distance, to more than 270 m. This defines a subsurface of high sediment thickness that extends across the entire study area from west to east and underlies south-central Bam. Therefore, based on a positive relationship between the damage rate and alluvial thickness (Rezaei et al., 2009;Marie Nolte, 2010), MF for this criterion is depicted in figure 5a.

- Consolidation and strength of soil and sediments: It has been frequently observed that earthquake damage is greater in settlements located on unconsolidated and soft soils than in those sited on stiff soils or hard rock. For example, in Bam earthquake strong amplification occurred due to the extremely soft clay layers that caused high-rise buildings to collapse (Jafari et al., 2005). Another example was the Loma Prieta earthquake that happened in 1989, where much of the damage occurred in the central San Francisco Bay area at sites underlain by thick deposits of soft clay soils (Stewart, 1997). The soil classification has been based on different thresholds for the average shear wave velocity (Vs) to a depth of 30m by the National Earthquake Hazard Reduction Program (NEHRP) to characterize sites for purposes of estimation amplification of seismic motions. This standard has applied in Unified Building Code (Dobry et al., 2000) and Eurocode8 (Sabetta and Bommer, 2002;Kanlı et al., 2006). Based on this classification in areas on unconsolidated sediments, shear wave velocity reduces, and expected amplification during earthquakes could be increased. Therefore, according to this MFs for each class have been calculated as shown in figure 5b.

- Type of soil and particle size distribution of sediments: It has long been recognized that the destructiveness of ground shaking during earthquakes can be significantly worsened by the type of local soil and subsurface sediment conditions. In past events, the observed variability in seismic intensity and structural damage severity has often been attributed to the variability of soil and subsurface sediment stratigraphy in a given area. Among the geotechnical properties of soil and sediments, grain size is one of the most important criteria (Assimaki et al., 2006;Phoon et al., 2006). In the study area, Rezaei et al. (2009) identified eight sediment types: clay, silt, sand, granules, pebbles, cobbles, and boulders. They stated that the grain size in the shallow subsurface (<10 m) decreases across the city from south to north and increases with depth. Their investigation showed that fine-grained soils and sediments (clay, clayey sand, cohesive sandy mud, and cohesive muddy sand) dominated the northern part of the city at shallow depths. In the central part of the city, fine-grained sediments changed laterally to coarse-grained sediments (poorly sorted sand, well-rounded gravel, poorly sorted gravel, and muddy or sandy gravel) which dominated in the south part of the city. As a rule, it can be assumed that, the smaller the grain size of sediments, the less the shear waves velocity and therefore the greater the effect of the seismic wave on the destruction level of buildings (Rezaei et al., 2009;Assimaki et al., 2006;Phoon et al., 2006). Therefore, the MFs for each specific grain size are calculated in figure 5c.

- Depth of groundwater: Research on the effects of groundwater shows it can magnify an earthquake’s damage. The most well known effect is liquefaction. The geologic and hydrologic factors that affect liquefaction susceptibility are the age and the type of sedimentary deposits, the looseness of cohesions and the depth to the groundwater table (Tinsley et al., 1985;Cavallaro et al., 2018). The liquefaction is mostly limited to water-saturated, cohesions less sediments and granular sediments at depths less than 15m (Iguchi and Tainosho, 1998;Sitharam, 2010). Noack and Fah (2001) categorized it by the depth of the water table, which is split into three classes where the weight of the class increases while the groundwater table decreases (Fäh et al., 1997). Therefore, due to the geological conditions in Bam, liquefaction is considered of minor importance because Talebian et al. (2004) and Rezaei et al. (2009) found water saturated sands in very few places, however, they reported high amplification in areas that groundwater level was very close to the ground surface by analyzing microtremore data. Accordingly, MFs for each class of groundwater depth are computed as shown in figure 5d.

- Type of rock: Type of rocks can effect on local seismic amplification susceptibility in a region. Three main types of rock based on their formation process include igneous, metamorphic, and sedimentary rocks. Each type has its own sub-categories and what matter in this research is how hard or soft and how dense the specific type of rocks is in comparison with the other types. Geological Strength Index (GSI) of “rock masses depends on rock’s material, the amount of joints and their relations, alteration, and presence of water” (Hoek and Brown, 1997). There are many rock types in the nature that GSI can be calculated for any of them based on their condition, and then can be fuzzified addressing their effect on seismic microzonation level of ground shaking. There are five classes of GSI including very good, good, fair, poor and very poor based on their surface quality and interlocking of rock pieces from massive, blocky, very blocky, disintegrated, and laminated/ sheered (Marinos et al., 2007). The GSI values categorized in five classes including very low, low, medium, high and very high levels. These classes shows the geological strength of rocks that the high and very high GSI demonstrate high to very high strength of rocks. Therefore, previous studies demonstrates that in massive rocks, high GSI values, seismic waves passes quickly and therefore have small influence in seismic microzonation level of ground shaking, and vice versa if GSI value gets to the lower values. Thus, in fuzzyfication process of surficial rocks, the rock with very high GIS assign 0 and the rocks with very low GSI assign 1 (Figure 6a). Furthermore, the criterion of type of bedrock acts the same as surficial rock type criterion as explained above. Type of bedrock rarely changed over a small extent with homogenous lithology. However, it was concern of experts in determining local seismic amplification susceptibility.

- Slope: The effects of slope angle on topographic amplification factor was investigated by Bisch et al. (2012), and they classified the slope angle into three categories with different effect level including: 0-15 with no effect, 15-30 degree with 1.2 (coefficient) and more than 30 degree with 1.4 amplification coefficient. Although, Cavallaro et al. (2012) suggested that topographic amplification factor can be considerable for slope even less than 15 degree. Furthermore, Bouckovalas and Papadimitriou (2005) investigated the influence of slope topography in amplifying the peak horizontal seismic ground acceleration suggesting high amplifications near the crest. Grelle et al. (2016) presented formulae for topographic amplification on slope surface. These studies indicated that with the increase in slope angle the amplification factor would increase. This can be a basis for depicting MFs of this criterion (Figure 6b).

- Topographic irregularities: Seismic amplification has been witnessed in several earthquakes due to topographical changes (Geli et al., 1988;Paolucci, 2002;Cavallaro et al., 2012). Bisch et al. (2012) classified the site in two classes of “isolated cliff and ridge with crest width significantly less than base width” (CEN European Committee for Standardisation, 1994, p 93). However, this seems simplistic, as it does not consider the elevation differences. Furthermore, Grelle et al. (2016) presented an equation that considered the local slope height, relief height, regional share wave velocity and relief ratio. In addition, several calibration constants should be calculated using 2d numerical analysis for each study area to compute topographic effects on local seismic amplification. Cavallaro et al. (2008) investigated 2d model for analysing site response of the Monte Po Hill in the City of Catania considering the effect of topographic and stratigraphic properties on the amplification factor in an area. They concluded that near to the slop crest, the effect of topographic properties on amplification factor is more relevant than stratigraphic property. Lee et al. (2009) found out that the amplification on top of elevated surfaces with small extent was much higher than valleys and flat areas. Therefore, the elevation differences (dH m) between the bases of a hill to the top of the hill, and the area (A m^2) of the top part of the hill are the main driver in computing the amplification coefficient of seismic waves that can effect on local seismic amplification susceptibility level of ground. Therefore, the higher the elevation differences and the smaller the area of the elevated surface, the ground in this part will be more amplified. Here, using fuzzy logic and experts' knowledge the effect of topography in terms of elevation differences in determining local seismic amplification susceptibility in the study area is defined (Figure 6c).

Figure 5. Membership functions (MFs) based on fuzzy logic system: Thickness of soil and sediments (a), Consolidation and strength of soil and sediments (b), Type of soil and particle size distribution of sediments (c), Depth of groundwater (d).

Figure 6. Membership functions (MFs) based on fuzzy logic system: Type of rock and bedrock (a), Slope (degree) (b), Topographic irregularities (c).

2.3.3. Preparing thematic data

The required data were collected from relevant organizations and documents and they were converted to GIS files in that papered maps were scanned, geo-referenced and then digitized. These maps were imported into a geodatabase to validate topological rules and overlaying condition for all layers. To produce thematic maps, interpolation method such as IDW method was applied. The produced maps then were classified based on sub-criteria for each criterion, then they were reclassified and converted to raster layers enabling raster combination of all layers to each other. These thematic data included: alluvial thickness (Figure 7a), stiffness and strength of soil and sediments (Figure 7b), type of soil and particle size distribution of soil and sediments (Figure 8a and b), depth of groundwater (Figure 9a), type of rock (Figure 9b), topographic irregularities (Figure 10a), and slope (Figure 10b) layers.

Figure 7. Thematic Layers of Bam city: Alluvial thickness (m) (a), Stiffness and strength of soil and sediments (b).

Figure 8. Thematic Layers of Bam city: Sediment type at depth of 1 meter (a) and at depth of 9 meters (b).

Figure 9. Thematic Layers of Bam city: Groundwater level (a), Type of rock (b).

Figure 10. Thematic Layers of Bam city: Topographic irregularities (a) and Slope (b).

2.3.4. Preparing control data

National Cartographic Center (2003) and Hisada et al.(2005) were collected data on the destruction level of buildings after math of the Bam earthquake (Figure 11a and b). Lashkari Pour et al. (2006) and Motamed et al. (2007) were collected data on the dominant frequency of soil (Figure 12a and b) and amplification factor by Motamed et al. (2007) (Figure 13) using microtremor measurements in Bam city. These datasets were classified to 5 classes based on equal interval classification method including very low, low, moderate, high and very high classes. Then, they were applied to validate the model's output through a comparison analysis and calculating overall accuracy and kappa coefficient.

Figure 11. Control data: Actual building destruction level (Hisada et al., 2005) (a), percentage of damage to buildings caused by the Bam earthquake in 2003 (National Cartographic Center of Iran (NCCI), 2003) (b).

Figure 12. Control data: Dominant frequency by (LashkariPour et al., 2006) (a) and by Motamed et al. (2007) (b) using Microtremor field measurement.

Figure 13. Control data: Amplification factor by Motamed et al. (2007) using Microtremor field measurement.

2.3. Spatial combination methods and overlay rules

The spatial Multi Criteria Decision Making (MCDM) approach is a decision-aid and a mathematical tool that combines and transforms spatially referenced data into a raster layer with a priority score. (Roy, 1996;Malczewski, 2006). Several combination methods have been developed, such as Boolean operations (Malczewski, 1999), weighted linear combination (WLC: combining the normalized criteria based on overlay analysis) (Voogd, 1983;Drobne and Lisec, 2009;O'Sullivan and Unwin, 2010) (Eq. 5), ordered weighted averaging (OWA) (Yager, 1988;Rinner and Malczewski, 2002), and Analytical Hierarchy Process (AHP) based on the additive weighting methods (Zhu and Dale, 2001). In this research, the AHP method (Saaty, 1980) was used to derive the weights associated with criteria and Fuzzy Logic method was applied to compute sub-criteria's membership functions (MFs) in order to produce the local seismic amplification. Then, the degree of membership of each sub-criteria (calculated by Fuzzy Logic method) is assigned to the corresponding sub-criteria. Next, this is multiplied by the weight of corresponding criteria (calculated by AHP method). Finally, they are summed up in a linear manner using WLC method (Eq. 5) to develop the model (Larzesh model) for production of the local seismic amplification in the study area.

$$Ai = \sum W_j \, * \, X_{ij} \qquad \textit{(Eq. 5)}$$

Where: w_j = the calculated weight of criteria j, and Xij = the degree of memebrship of the ith sub-criteria with respect to the jth criteria, and Ai = the local seismic amplification index in ith location.

2.4. Validation and comparison methods

In order to validate the model, as categorical variables are the main driver of model development in this research, therefore relevant measures such as Overall Accuracy and Kappa statistic will be applied to measure the performance of the model.

a) Overall accuracy (OA)

Accuracy assessments determine the quality of the results derived from data analysis or a model, in comparison with a reference or ground truth data (where ground truth data are assumed to be 100% correct) (Congalton and Green, 2009). The accuracy assessment can be obtained by creating a contingency table of counts of observations, with calculated, estimated or predicted data values as rows and with reference data values as columns. The values in the shaded cells along the diagonal represent counts for correctly classified observations, where the reference data matches the predicted value. This contingency table is often referred to as a confusion matrix, misclassification matrix, or error matrix (Czaplewski, 1992;Congalton and Green, 2009) (Eq. 6).

$$OA = \frac{\sum_{k=1}^{q} n_{kk}}{n} \times 100 \qquad \text{(Eq. 6)}$$

Where: OA = Overal Accuracy, n_{kk} = Values in diagonal cell of the matrix (correctly classified observations), and n = number of observations.

b) Kappa analysis

The kappa statistic (κ) (Sim and Wright, 2005;Congalton and Green, 2008) calculates degree of agreement between classes of two independent observe measuring the same property. The degree of Kappa would be 0 for a random classifies and 1 for classification. Degree of agreement of Kappa interprets as follows: less than 0.4: poor agreement, 0.4 and 0.8: moderate agreement, and greater than 0.80: strong agreement (Congalton and Green, 2008) (Eq. 7).

$$k = \frac{P_o - P_e}{1 - P_e} \qquad \text{(Eq. 7)}$$

Where: Po = the relative observed agreement among raters, Pe = the hypothetical probability of chance agreement.

Results and discussion

In order to produce the local seismic amplification susceptibility the most important criteria were identified and then were weighted using AHP pair-wise comparison method. The higher weight belong to alluvial thickness (0.271), stiffness and strength of soil and sediments (0.207), type of soil and particle size distribution of sediments (0.177), depth of groundwater (0.171), topographic irrigularities (0.054), type of rock (0.041), slope (0.040), and type of bedrock (0.040) were considered. Then, based on Fuzzy Logic method sub-criteria of each criterion was fuzzified and membership functions for them was defined. Next, these criteria were combined based on the Weighted Linear Combination (WLC) (Drobne and Lisec, 2009) in GIS to develop the model for producing the susceptibility map of local seismic amplification for the study area, as it is proposed in the following (Eq. 8):

$$A_j = \sum(wS_s \,.\, FS_{ss}) + (wT_A \,.\, FS_{TA}) + (wS_A \,.\, FS_{SA}) + (wD_{Gw} \,.\, FS_{DGW}) + (wT_R \,.\, FS_{TR})$$

$$+(wT_{Br} \,.\, FS_{TBR}) + (wT_S \,.\, FS_{TS}) + (wS_L . FS_{SL}) \qquad \textit{(Eq. 8)}$$

Where: A_j *= local seismic amplification susceptibility, weights of each criterion:* wS_s *= stiffness and strength of soil and sediments ,* wT_A *= Alluvial thickness,* wS_A *= Type of soil and particle size distribution of sediments ,* $wD_{Gw} = depth\ of\ groundwater$ *,* wT_R *= type of rock ,* wT_{Br} *= type of bedrock,* wT_S *= topographic irregularities,* wS_L *= slope, and fuzzified sub-criteria of each criterion:* FS_{ss} *= stiffness and strength of soil and sediments,* FS_{TA} *= Alluvial thickness,* FS_{SA} *= Type of soil and particle size distribution of soil and sediments,* $FS_{DGW} = depth\ of\ groundwater,$ FS_{TR} *= type of rock ,* FS_{TBR} *= type of bedrock,* FS_{TS} *= topographic irregularities, and* FS_{SL} *= slope.*

Figure 14 displays the resulting microzonation map of ground shaking in Bam city. The areas with high to very high susceptibility to local seismic amplification are located in the north, east and northeast part of Bam city. This is due to the widespread unconsolidated sediments, low groundwater level in combination with high sediment thickness.

In order to validate the results, OA and Kappa methods were applied comparing the output of model with the measured predominant frequency (Askari et al., 2004;LashkariPour et al., 2006;Motamed et al., 2007) in the study area. The results demonstrated 73.6% and 82% (Table 4a and b) for OA and 0.74 and 0.75 for Kappa (Table 5) indicating a good fit of the model's output with the measured data. Moreover, the overlay of the building destructions caused by the Bam earthquake in 2003 (Hisada et al., 2005;National Cartographic Center of Iran (NCCI), 2003) shows that high destruction levels happened in locations with high ground shaking which were located in central, north and northeast part of the city.

Figure 14. Susceptibility map of local seismic amplification of Bam city

Table 4. Comparison between the model's output with the measured predominant frequanecy in Bam city by Motamed et al. (2007) (a)c and LashkariPour et al. (2006) (b).

Table 5. Kappa coefficient and OA

In this study, we have focused on the site effect and local geology properties of a site that have a massive influence on local seismic amplification susceptibility in the study area. To deal with related uncertainties in preparing seismic microzonation, the most important criteria were selected, weighted and then fuzzified. Criteria with high uncertainty degree such as distance of active fault to the site, depth and magnitude of the probable earthquake were not considered because there was no possibility to exactly find out where and how an earthquake will be triggered. Therefore, only the criteria with known location (x and y) and known characteristics were taken into consideration. Furthermore, to deal with uncertainties Fuzzy Logic is a suitable approach as we can define membership function of the effect of each criterion in the amplification of ground shaking by interviewing 10 experts and obtaining expert's knowledge. This can result in realistic output regarding the behavior of each criterion in ground shaking calculation.

The newly developed model uses AHP and Fuzzy Logic (Zadeh, 1965) to deal with complexities and uncertainties in data analyses in weighting the criteria and fuzzifying the sub-criteria of each criterion. Although, in studies for evaluating seismic microzonation in Bangalore (India) (Sitharam and Anbazhagan, 2008), Dehli (Mohanty et al., 2007), Haldia (India) (Mohanty et al., 2007), Erbaa (Turkey) (Akin et al., 2013) and Al-Madinah (Moustafa et al., 2016) only AHP method was applied to weight the criteria, and none of these studies considered weighting of sub criteria for each criterion even using other methods.

Few researchers have considered direct properties of influencing factors in assessing ground shaking amplification. Even, in evaluating seismic response developed models such as SiSeRHMap v1.0 (Grelle et al., 2016) and GIS Cubic Model (Grelle et al., 2014), the researchers have applied only lithodynamic, stratigraphic and topographic effects as influencing factors. Furthermore, Aucelli et al. (2018) suggested a method for producing susceptibility index to local seismic amplification in Isernia Province, Italy, and they have considered geological and geomorphological properties of studied areas. Although, they have not considered the use of multi-criteria decision-making methods (MCDM) in weighting and combining the influencing criteria which is the aim of current study. The current research considers direct properties of each criteria and tries to manage uncertainties in criteria and sub-criteria of each criterion via weighting and fuzzification process using experts' knowledge and the use of direct properties of criteria. These processes can be extended in more details, which are subject to more investigation in the future.

Conclusions

Larzesh model introduces a new method based on AHP and Fuzzy Logic rules that enables experts to produce local seismic amplification susceptibility using direct properties of lithological, sedimentological, geological, hydrological and topographical effects in a study area using experts' knowledge in weighting and fuzzifing criteria and sub criteria that can be readily perceived and consulted.

The application of the model was carried out in the urban area of the Bam city in Iran. The results demonstrated high to very high ground shaking amplifications were located in central, east, and northeast to north part of the city that was confirmed comparing with measured microtremor data on predominate frequency in the study area. However, as the proposed model is a spatial computational tool, the validation of output in producing local seismic amplification strictly dependent on the quality and preparation of input data.

In conclusion, the model enable disaster managers, planners, and policy makers in producing local seismic amplification susceptibility and making informed decision in urban planning and designing appropriate plans for urban development, especially in areas with high seismic activities.

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Tables

Table 1.Relevant criteria that influence on seismic microzonation

1	Alluvial thickness	9	Thickness of bedrock
2	Stiffness and strength of alluvial deposits	10	Morphology of bedrock
3	Type of soil and particle size distribution of alluvial deposits	11	Topographic irregularities of bedrock
4	Depth of groundwater	12	Age of alluvial deposits
5	Topographic irregularities	13	Age of bedrock
6	Type of rock	14	Age of rock
7	Slope		
8	Type of bedrock		

Table 2.The average importance criteria based on 5-point Likert Scale

	Criteria for	Average
1	Alluvial thickness	8.5
2	Stiffness and strength of alluvial deposits	8
3	Type of soil and particle size distribution of alluvial deposits	7.5
4	Depth of groundwater	7.25
5	Type of rock	7
6	Topographic irregularities	5.25
7	Slope	5
8	Type of bedrock	5
9	Thickness of bedrock	4.5
10	Morphology of bedrock	4.5
11	Topographic irregularities of bedrock	4.5
12	Age of alluvial deposits	3.75
13	Age of bedrock	3.25

14	Age of rock	2.75

Table 3.The results of pair-wise comparisons of the selected criteria with each other based on the AHP matrix

Criteria	1	2	3	4	5	6	7	8	Weights
1- Alluvial thickness	1	1	2	2	5	5	7	4	0.271
2- Stiffness and strength of alluvial deposits		1	1	1	5	4	5	5	0.207
3-Type of soil, and particle size distribution of alluvial deposits			1	1	5	5	5	7	0.177
4-Depth of groundwater				1	5	7	3	5	0.171
5-Type of rock					1	2	1/2	1/2	0.041
6-Topographic irregularities						1	1/2	3	0.054
7-Slope							1	4	0.040
8-Type of bedrock								1	0.040
Lambda = 8.60 CI = 0.05									

Table 4. Coparesion between the model's output with the measured predominant frequanecy in Bam city by Motamed et al. (2007) (a) and LashkariPour et al. (2006) (b).

a)

	Predominant Frequency (Measured)					
Predicted	**1**	**2**	**3**	**4**	**5**	**Total**
1	1	1			1	3
2		3		3		6
3	1		6	1		8
4		1		9		10
5			2		9	11
Total	**2**	**5**	**8**	**13**	**10**	**38**
Av_Ac = 73.6 %						

b)

	Predominant Frequency (Measured)					
Predicted	**1**	**2**	**3**	**4**	**5**	**Total**
1	1					1
2		1				1
3			3			3
4				1		1
5	1			1	2	4
Total	**2**	**1**	**3**	**2**	**2**	**10**
Av_Ac = 80 %						

Table 5. Kappa coefficient and OA

Comparison of the model's output and measured data	Predominant frequency (Motamed et al., 2007)	Predominant frequency (LashkariPour et al., 2006)
Kappa coefficient	0.74 (0.000)	0.75 (0.000)
OA	73.6%	80%

Figures

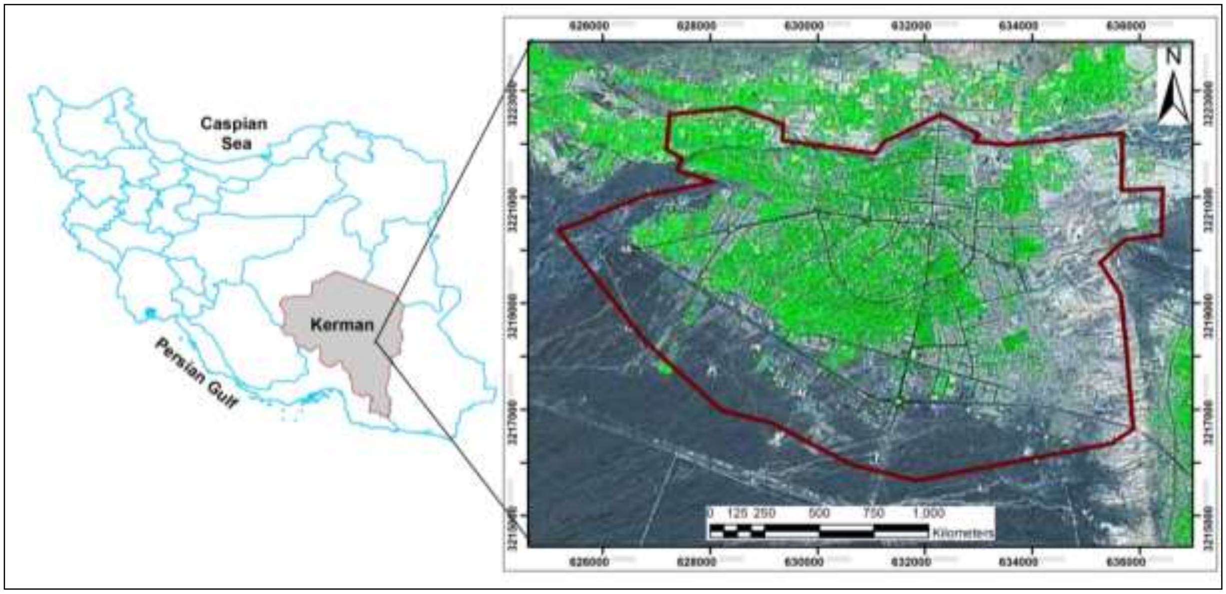


Figure 1. The case study area of Bam City, Iran

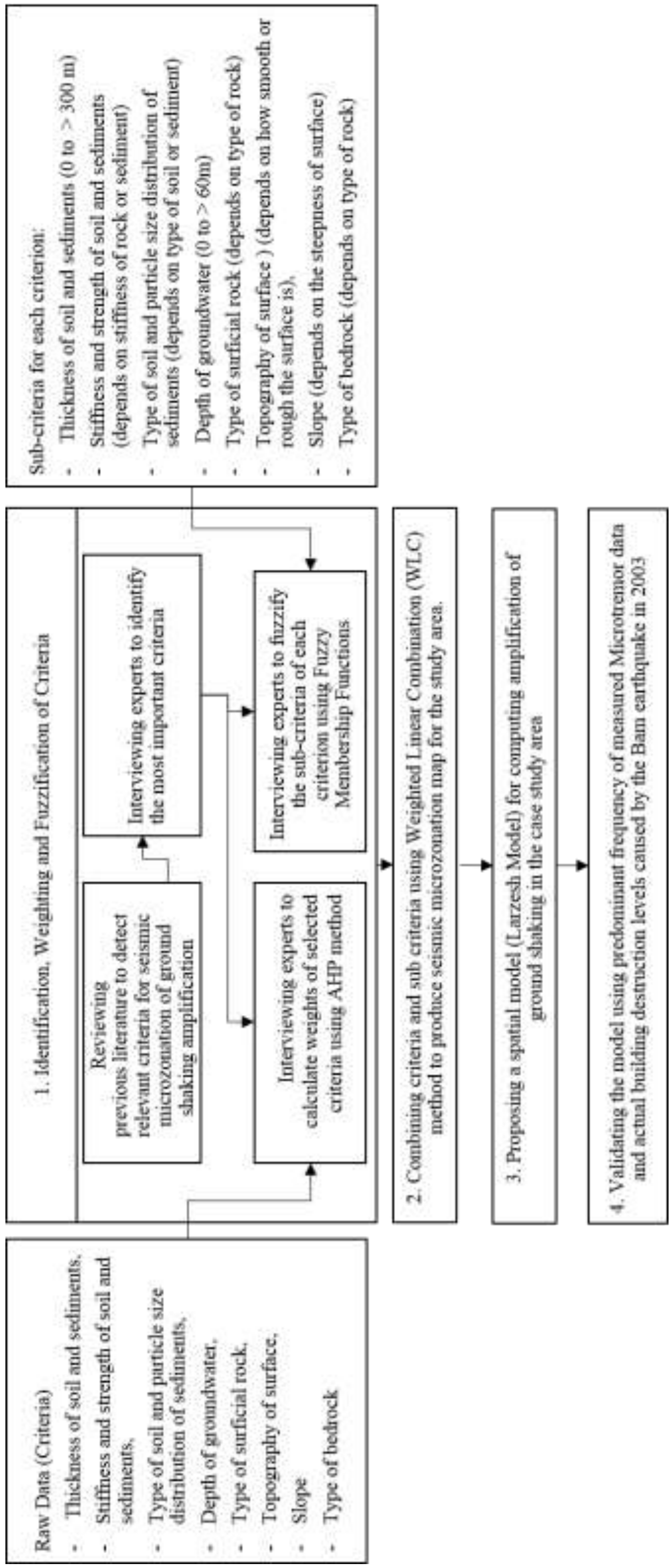


Figure 2. The methodological approach of the model

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

Where: $a_{ij} = 1, if\ i = j,\ and\ a_{ij} = \frac{1}{a_{ij}}, if\ i = \overline{1,n}\ and\ j = \overline{1,n}.$

Figure 3.AHP matrix (A)

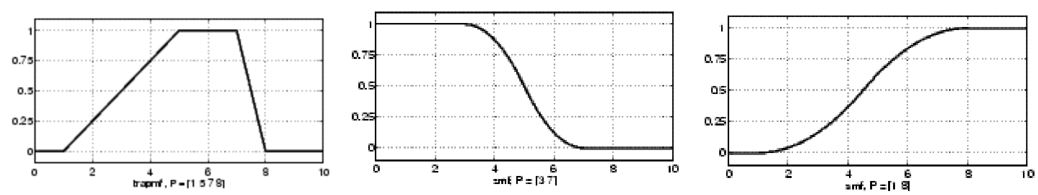


Figure 4. Fuzzy membership functions (After Mancini, 2012)

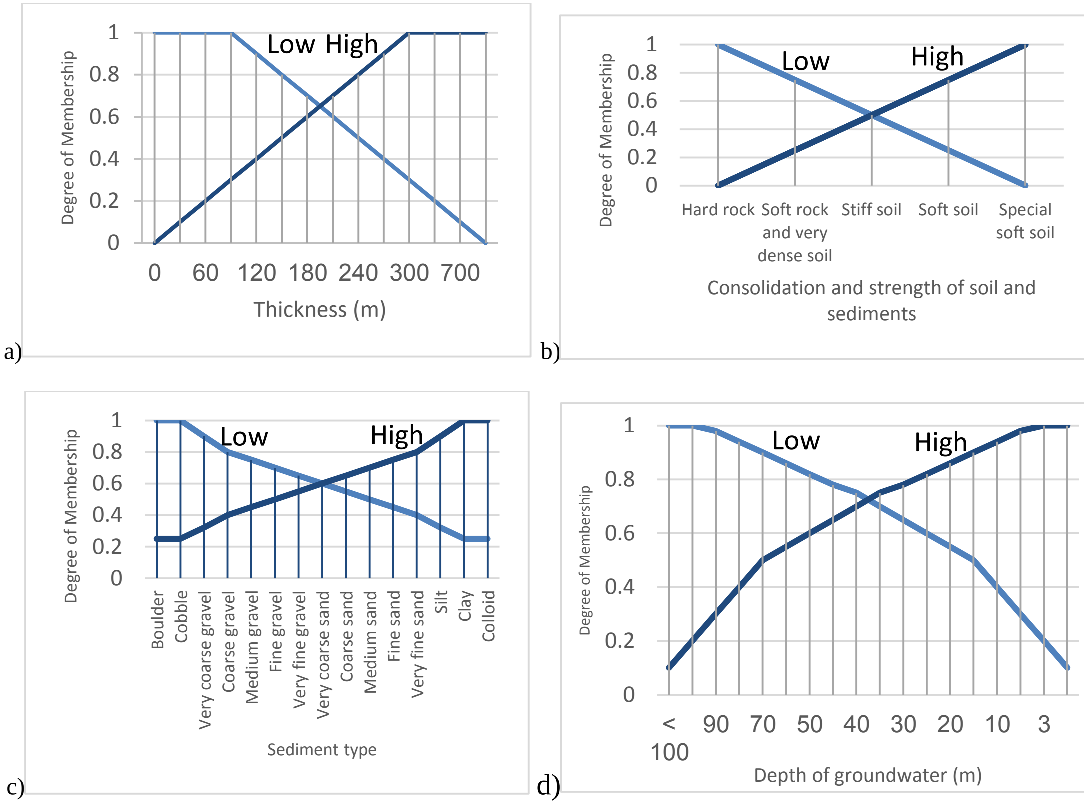


Figure 5. Membership functions (MFs) based on fuzzy logic system: Alluvial thickness (a), Stiffness and strength of soil and sediments (b), Type of soil and particle size distribution of sediments (c), Depth of groundwater (d).

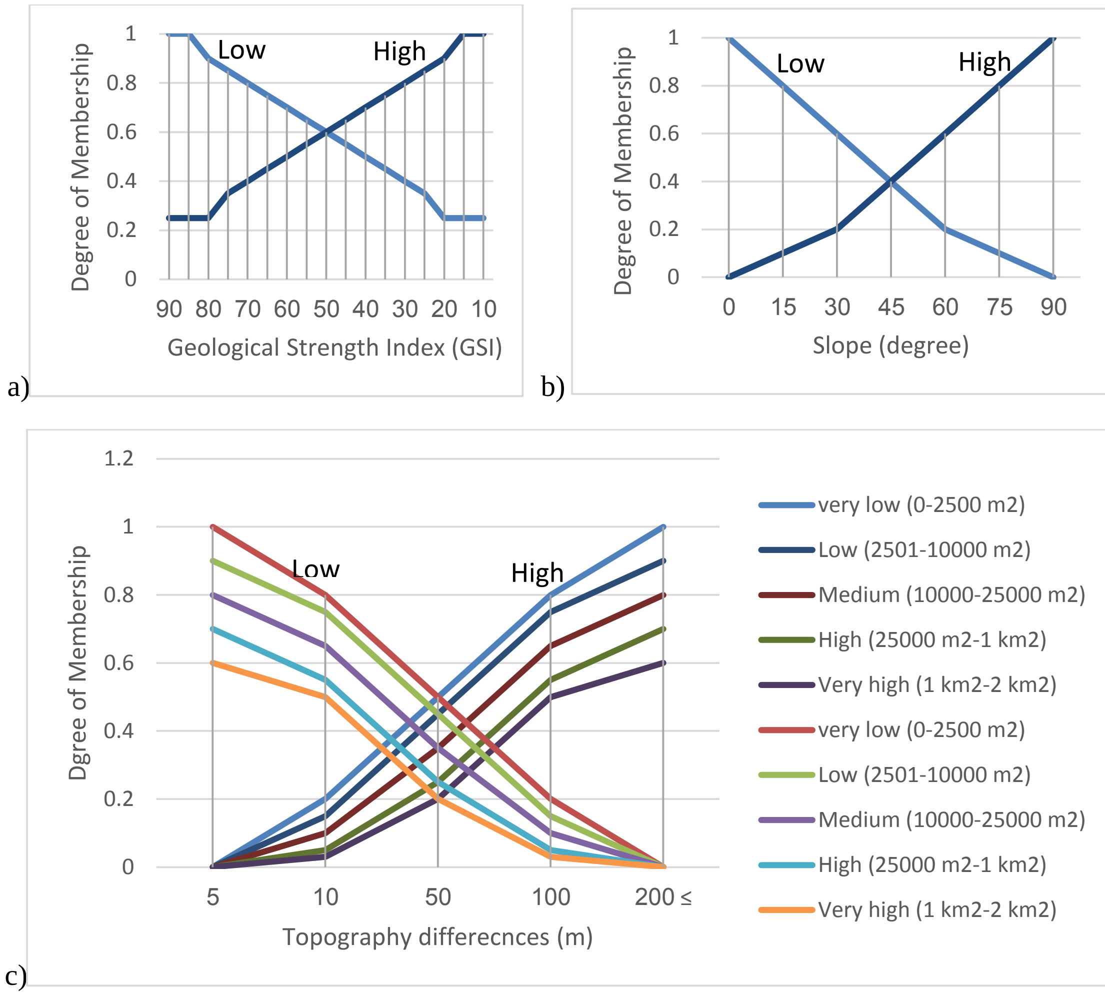
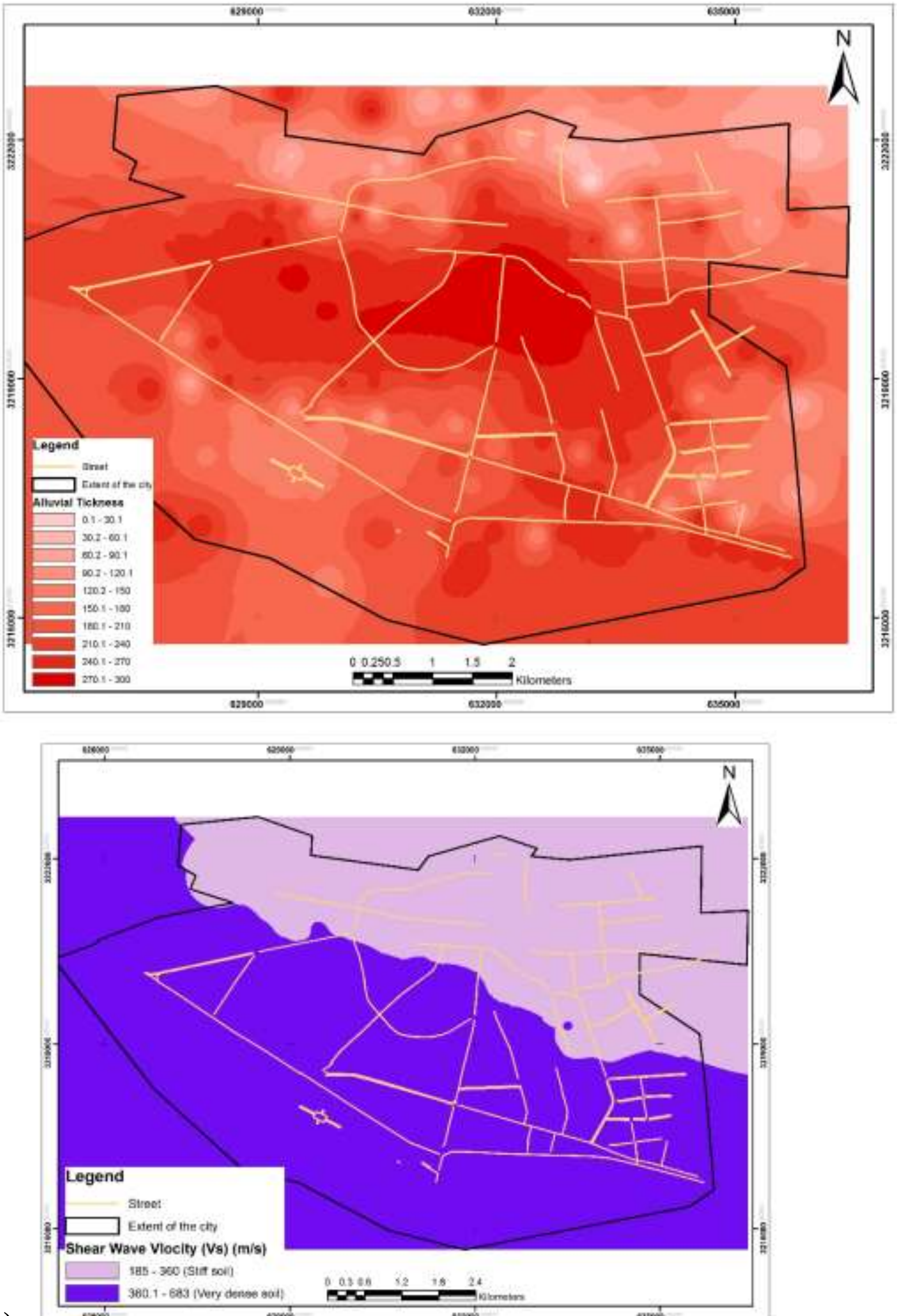


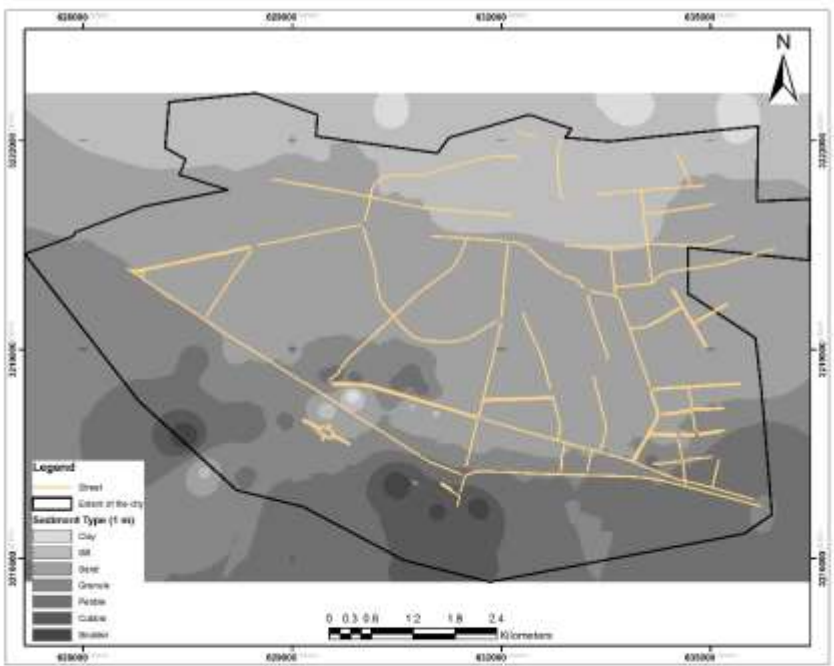
Figure 6. Membership functions (MFs) based on fuzzy logic system: Type of rock and bedrock (a), Slope (degree) (b), Topographic irregularities (c).



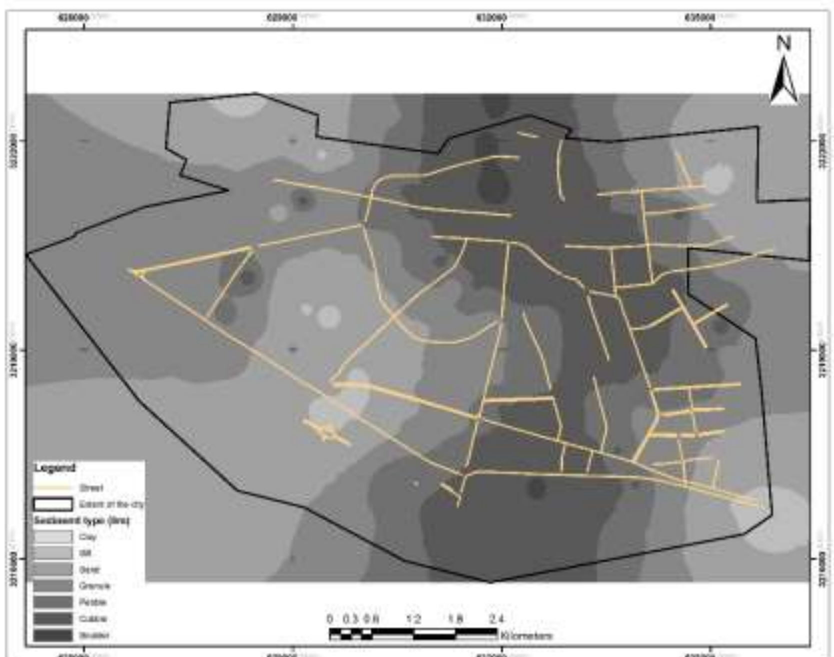
a)

b)

Figure 7. Thematic Layers of Bam city: Alluvial thickness (m) (a), Stiffness and strength of soil and sediments (b).

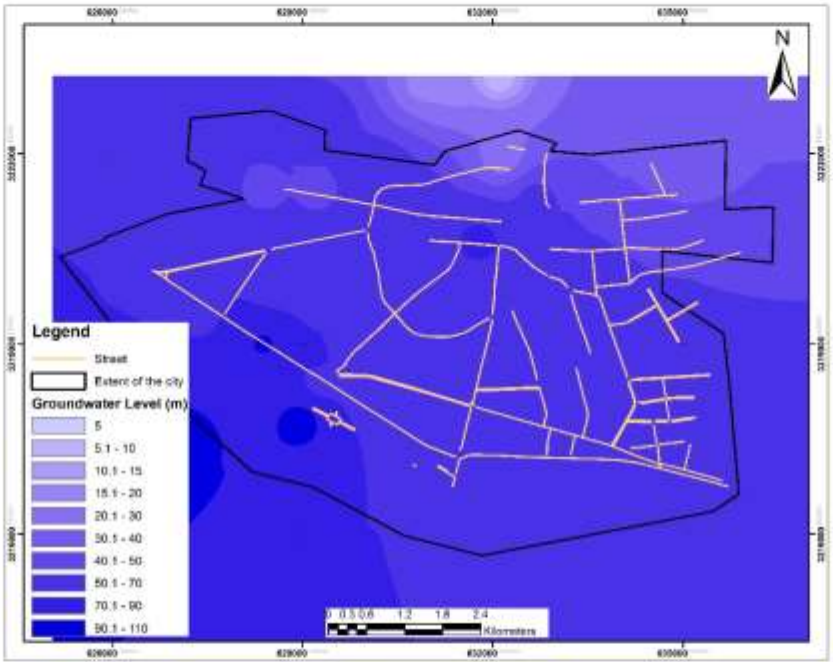


a)

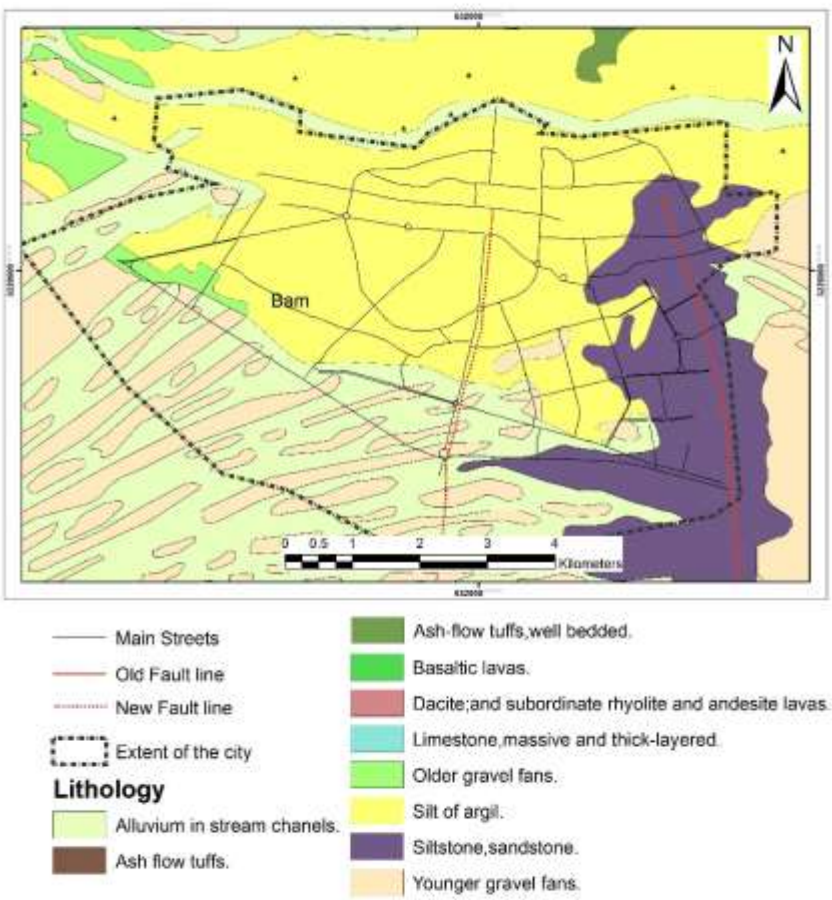


b)

Figure 8. Thematic Layers of Bam city: Sediment type at depth of 1 meter (a) and at depth of 9 meters (b).

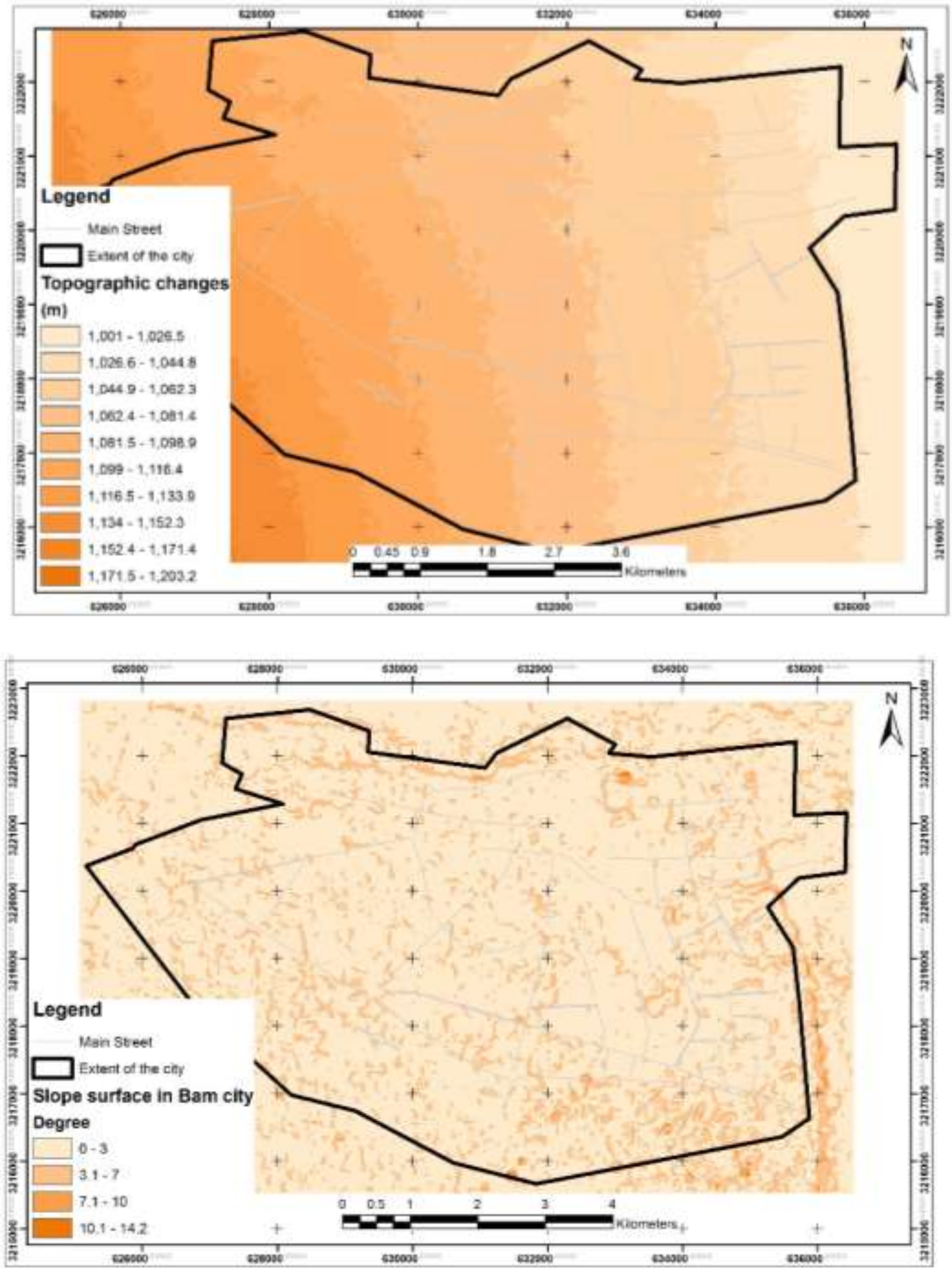


a)



b)

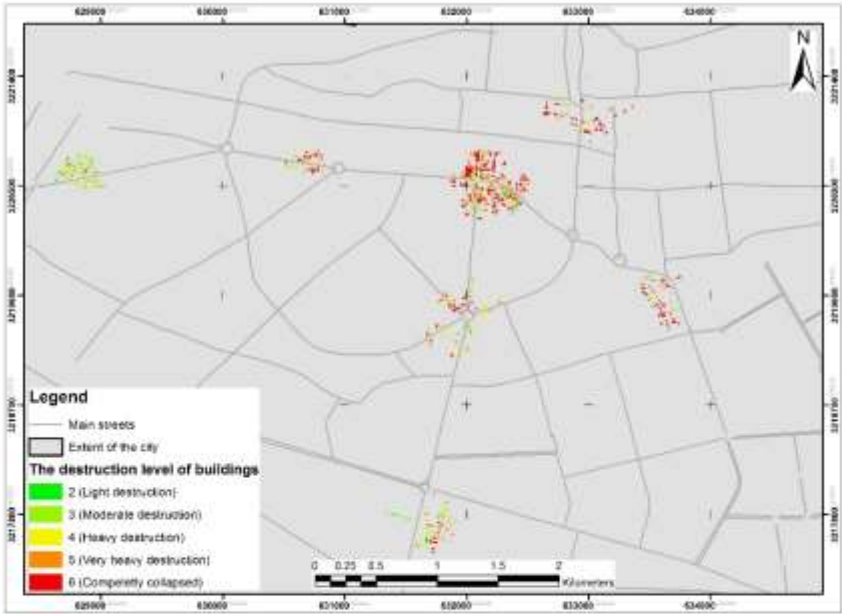
Figure 9. Thematic Layers of Bam city: Groundwater level (a), Geological map (type of rocks) (b).



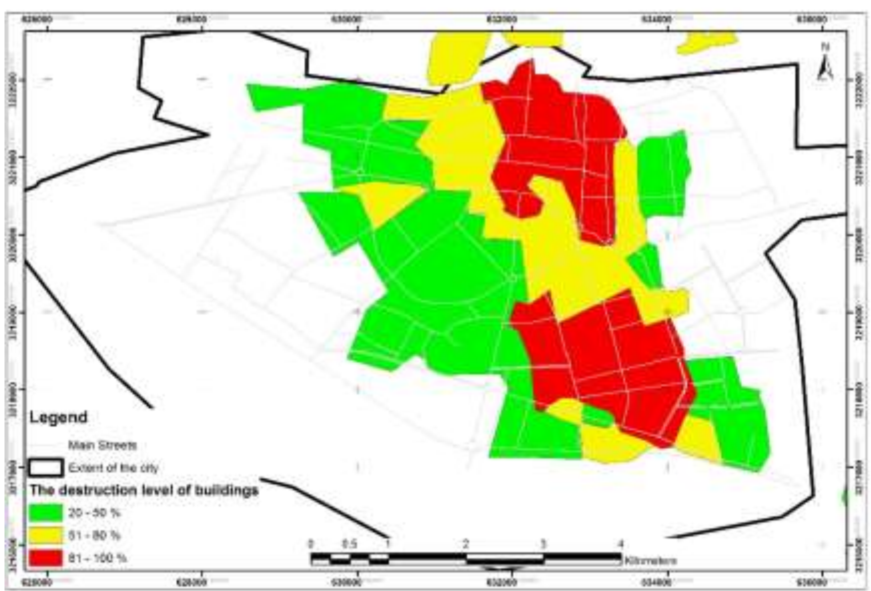
a)

b)

Figure 10. Thematic Layers of Bam city: Topographic irregularities (a) and slope (b).

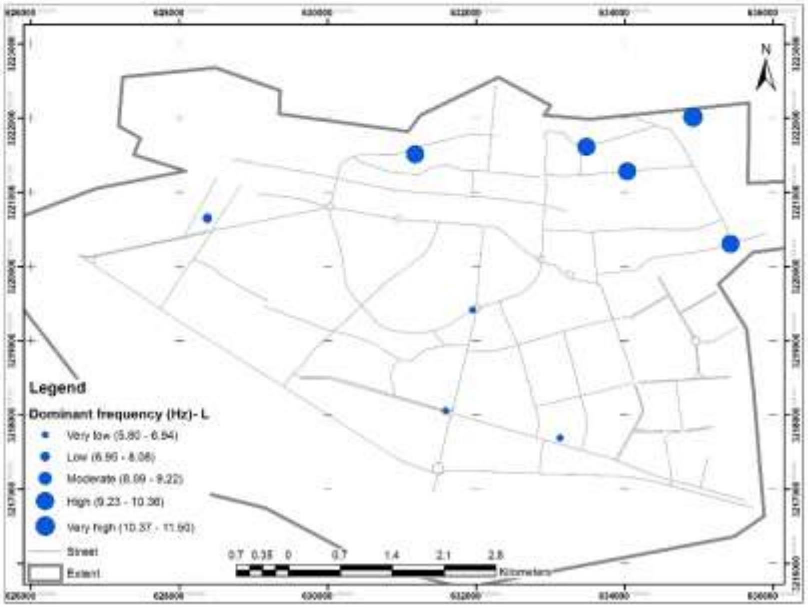


a)

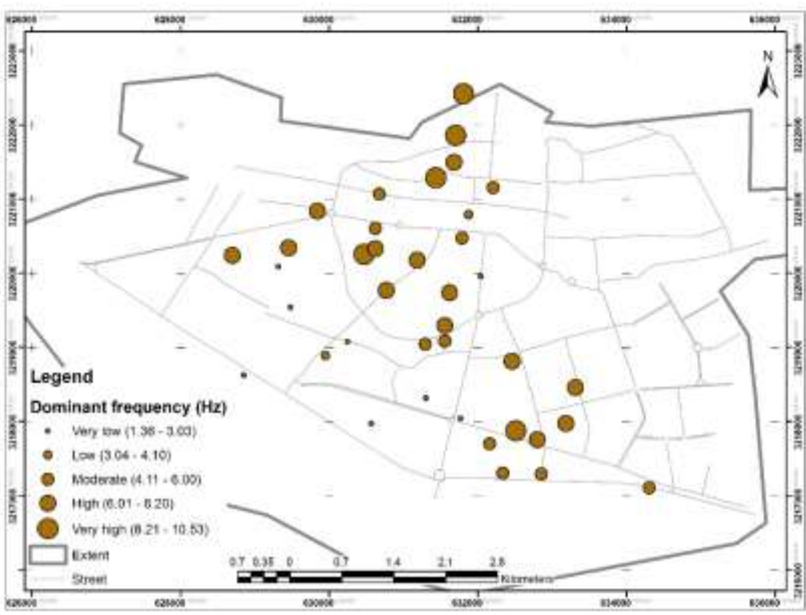


b)

Figure 11. Control data: Actual building destruction level (Hisada et al., 2005) (a), percentage of damage to buildings caused by the Bam earthquake in 2003 (National Cartographic Center of Iran (NCCI), 2003) (b).

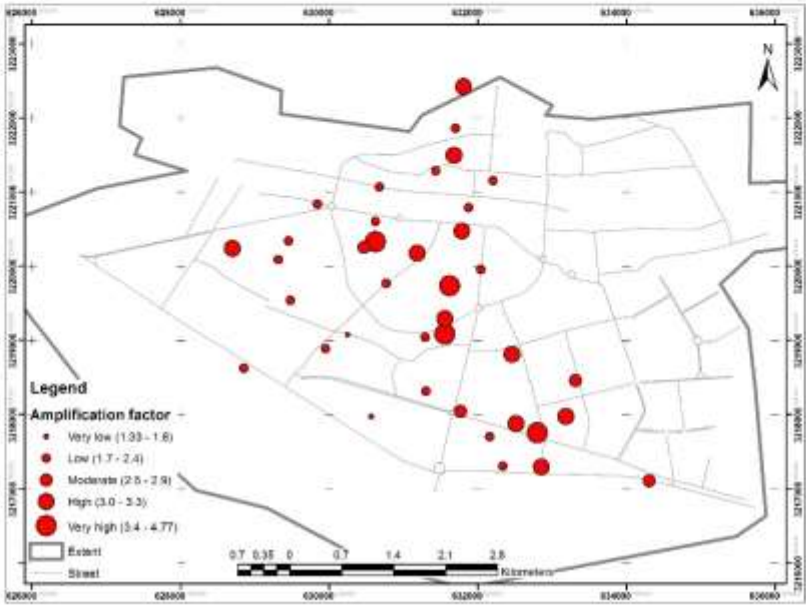


a)



b)

Figure 12. Control data: Dominant frequency by Lashkaripour (a) and by Motamed et al (Motamed et al., 2007) (b) using Microtremor field measurement.



e)

Figure 13. Control data: Amplification factor by Motamed et al. (2007) using Microtremor field measurement.

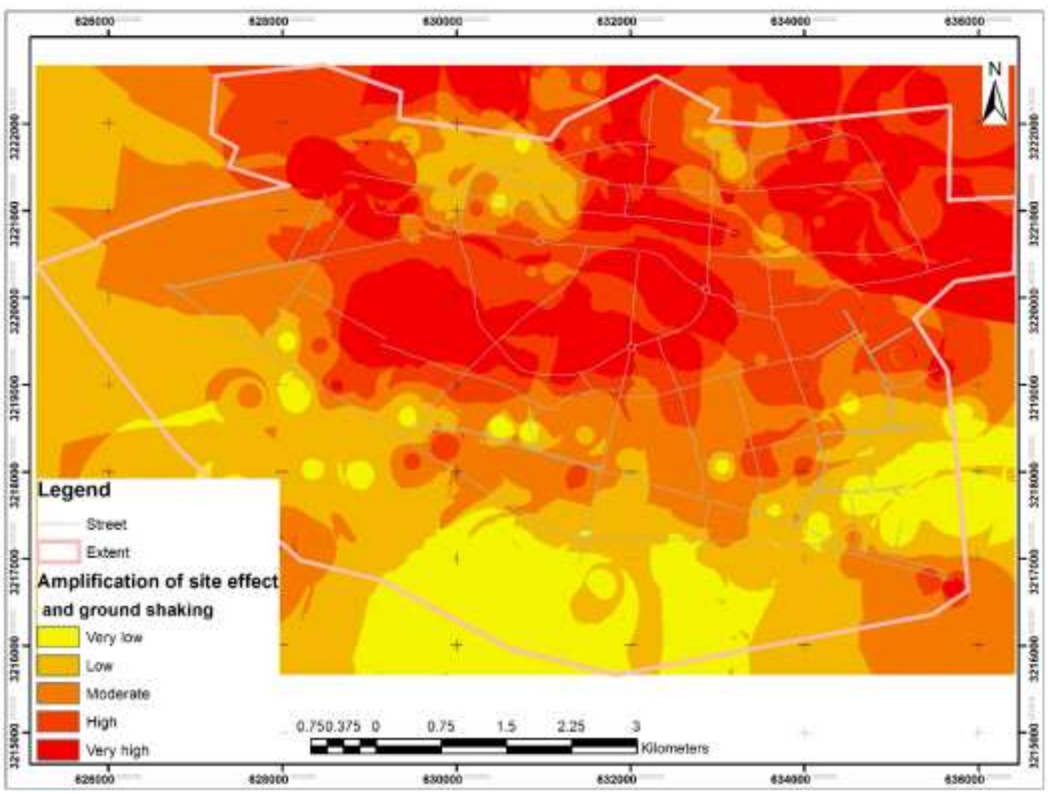


Figure 14. The susceptibility of local seismic amplification map in Bam city