١   **New approaches to modelling of local seismic amplification susceptibility using direct**

٢   **characteristics of influencing criteria: case study of Bam City, Iran**

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Abstract

١٤   This paper proposes a new model in evaluating local seismic amplification susceptibility by considering

١٥   direct characteristics of influencing criteria and it deals with uncertainty of modelling through production

١٦   of fuzzy membership functions for each criterion. For this purpose, relevant criteria were identified by

١٧   reviewing previous literature. These criteria include alluvial thickness, stiffness and strength of alluvial

١٨   deposits, type of soil and particle size distribution of alluvial deposits, depth of groundwater, type of rock,

١٩   topographic irregularities, slope and type of bedrock. Two methods, Analytic Hierarchy Process (AHP)

٢٠   and Fuzzy Logic (FL), were applied in order to define priority rank of each criterion and sub-criteria of

٢١   each criterion through interview data of 10 experts. The criteria and sub-criteria were combined using

٢٢   Weighted Linear Combination method in GIS to develop a model for assessing local seismic amplification

٢٣   susceptibility in the study area of Bam city, Iran. The model's output demonstrated high to very high

٢٤   seismic amplification levels in central, eastern, north-eastern and northern parts of the study area. The

٢٥   validation results based on overall accuracy and Kappa statistics showed 73.6% accuracy, 0.74 Kappa

٢٦   indicating a good fit to the model's output. This model assists planners and decision makers to produce

٢٧   local seismic amplification susceptibility to be incorporated in designing new development plans of urban

٢٨   and rural areas, and to facilitate making informed decision regarding safety measures of existing buildings

٢٩   and infrastructures.

٣٠   *Keywords: Seismic Amplification Susceptibility, Site Effects, Spatial Modelling, Analytic Hierarchy*

٣١   *Process, Fuzzy Logic and GIS.*

1.   Introduction

٣٦ This paper explores direct characteristics of influencing criteria in evaluating susceptibility of local

٣٧ seismic amplification and deals with uncertainty of modelling through production of fuzzy membership

٣٨ functions of each criterion. MERM microzonation manual (2003) sets different criteria effecting

٣٩ the amplitude and duration of ground shaking at a specific site. These include "the magnitude of

٤٠ the earthquake, focal point and depth of the earthquake, directivity of the energy released,

٤١ distance of rupture from the site, geological condition from the site to the location of the

٤٢ earthquake, local geological settings, geotechnical properties, and topographical condition of the

٤٣ site" (SM Working Group, 2015;Boore, 2003;Hassanzadeh et al., 2013;Castelli et al.,

٤٤ 2016a;Castelli et al., 2016b). It has long been known that local conditions of foundation soils

٤٥ have a significant impact on the effects of an earthquake on building destruction level, as it was

٤٦ demonstrated in previous earthquakes such as Mexico City, 1985 (Beck and Hall, 1986), Kobe,

٤٧ 1995 (Wald, 1996), Izmit, 1999 (Tang, 2000), Umbria-Marche earthquake, 1997 (Moro et al.,

٤٨ 2007) and Bam earthquake, 2003 (Ramazi and Jigheh, 2006) and L'Aquila earthquake, 2009

٤٩ (Monaco et al., 2012;Capilleri et al., 2014) and buildings that were located on unconsolidated

٥٠ sediments had greater destruction levels (Ramazi and Jigheh, 2006).

٥١ The aim of seismic microzonation studies is to produce ground-shaking map that can

٥٢ communicate efficient data to planners and policy makers in a geographic area to make informed

٥٣ decision regarding development policies in urban areas. Therefore, this community requires

٥٤ accurate information for developing mitigation plans and strategies. In the spite of this, there are

٥٥ uncertainties in determining local seismic amplification at a site, as this can be influenced by

٥٦ complex factors such as the earthquake source (epicenter of the earthquake), wave propagation

٥٧ and site condition. Uncertainty in these criteria results in uncertain ground-motion estimate from

٥٨ earthquakes (Wang et al., 2017;Wang et al., 2016;Petersen et al., 2016). There are different

٥٩ methods that have been used for assessing ground-motion hazards such as Probabilistic Seismic

٦٠ Hazard Analysis (PSHA), Deterministic Seismic Hazard Analysis (DSHA) and Scenario-based

٦١ Seismic Hazard Analysis (SSHA). Probabilistic Seismic Hazard Analysis (PSHA) method

٦٢ (Cornell, 1968;Atkinson et al., 2015;Petersen et al., 2016) depends on "the length of the causative

٦٣ faults and depth of the earthquake", which are generally unknown thus causing uncertainty in

٦٤ assessing ground-motion of earthquakes (Wang et al., 2017). In DSHA method (Campbell,

٦٥ 2003;Atkinson and Boore, 2006) lack of relevant ground-motion attenuation relationship for
٦٦ specific geographic areas can cause uncertainty in assessing ground motions of an earthquake
٦٧ (Wang et al., 2017). SSHA (Panza et al., 2012) applies ground-motion simulations of a scenario
٦٨ earthquake using specified source, path and site parameters, however the parameters needs to be
٦٩ defined in more details. By conducting many simulations, earthquake variability of different
٧٠ sources, ground-motion propagation characteristics, and local site effects can be considered.
٧١ Therefore, uncertainties using SSHA are quantified explicitly (Wang et al., 2017), although this
٧٢ method is still under development. Furthermore, Aucelli et al. (2018) proposed a method for
٧٣ producing susceptibility index to local seismic amplification in Isernia Province, Italy based on
٧٤ geological and geomorphological properties of studied areas. This research mostly followed an
٧٥ evidence based approach to estimate susceptibility level of local seismic amplification in the area,
٧٦ although they have not considered the use of multi-criteria decision-making methods (MCDM)in
٧٧ their study. Several MCDM methods have been developed to deal with ranking and weighting of
٧٨ criteria, such as Regime (Hinlopen et al., 1983), ELECTRE family (Figueira et al., 2005),
٧٩ Analytical Hierarchy Process (AHP) (Saaty, 1980), and Multiple Attribute Utility approach
٨٠ (MAUT) (Keeney and Raiffa, 1993). In this research, Analytical Hierarchal Process (AHP)
٨١ (Saaty, 1980) has been utilize as it is one of the most useful method in calculating criteria's
٨٢ weights, and AHP in combination with GIS were applied to produce seismic microzonation map
٨٣ of Bangalore (Sitharam and Anbazhagan, 2008) (2008), Dehli (Mohanty et al., 2007), Haldia,
٨٤ Bengal Basin (India) (Mohanty and Walling, 2008), Erbaa (Turkey) (Akin et al., 2013) and Al-
٨٥ Madinah (Moustafa et al., 2016) and generating ground-shaking map for Catania (Italy) using
٨٦ GIS (Castelli et al., 2016a). According to these methods experts evaluate and choose among
٨٧ qualitative and quantitative criteria. Since experts' judgments can be subjective and imprecise,
٨٨ uncertainty also exists in this analysis. Such uncertainties can be dealt with based on fuzzy logic
٨٩ principles (Zadeh, 1965) and inference systems (Klir, 2004;Zadeh, 1975).
٩٠ Fuzzy Logic method was used for evaluation of earthquake damage to buildings (Sen, 2010), and
٩١ evaluation of seismic microzonation (Teramo et al., 2005;Nath and Thingbaijam, 2009;Boostan
٩٢ et al., 2015). Although, there were a number of publications on evaluating the local seismic
٩٣ amplification in the literature, but few researchers have considered the use of Fuzzy Logic
٩٤ approach and direct characteristics of each criteria in evalaution of local seismic amplification
٩٥ susceptibility. These are motivations behind conducting this research.

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

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2. Material and methods

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

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١١٥ Figure 1. Case study of Bam City, Iran

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١١٧ Figure 2. The methodological approach of the study

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2.1. Identification, Weighting and Fuzzification of Criteria

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

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 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_{fij} 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)

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

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

 α_{ij}.

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

 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

١٥٥ alternatives (the weights) for each criteria. Therefore, in this research, AHP method is applied to

١٥٦ calculate the degree of importance of each criterion influencing on the susceptibility level of local

١٥٧ seismic amplification in a region,

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١٦١ **2.2.2. Fuzzy Logic (FL) method**

١٦٢ Fuzzy logic is a method of "approximating modes of reasoning" (Novák et al., 2012), and it is a

١٦٣ mathematical tool that deals with uncertainty in a different way that can relate independent

١٦٤ variables to dependent variables. Zadeh (1965) introduced Fuzzy set theory indicating that the

١٦٥ boundary is not precise and the gradual change is expressed by a membership function, and it

١٦٦ changes from non-membership to membership in a fuzzy set (Eq. 3). The characteristic function

١٦٧ value range between 0 and 1. Each membership function is represented by a curve that indicates

١٦٨ the assignment of a membership degree in a fuzzy set to each value of a variable. Curves of the

١٦٩ membership functions can be linear, triangles, trapezoids, bell-shaped, or have more complicated

١٧٠ shapes (Figure 4) depending on the purpose of the subject (Demicco and Klir, 2003).

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١٧٢ $A_a = \{x \, \mathcal{E} \, X \mid \mu_A \, (x) \geq a\}$ *(Eq. 3)*

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

١٧٤ element x.

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

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١٧٨ Fuzzy systems are mainly based on expert knowledge to formalize reasoning in natural language

١٧٩ mostly using sets of fuzzy inference rules or "*if–then*" rules (Eq. 4).

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١٨١ $If \; x \; is \; A \; then \; y \; is \; B$ *(Eq. 4)*

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١٨٣ As membership functions curve can easily be changed by small increments based on expert

١٨٤ knowledge, therefore, fuzzy logic can characterize and model geologic systems in an efficient

١٨٥ way (Klir, 2004;Demicco and Klir, 2003). Therefore, in this research using Fuzzy set, the

١٨٦ uncertainties in producing microzonation map of ground shaking can be managed by defining

١٨٧ fuzzy membership functions for each criterion. This happens by assigning meaningful values (0

١٨٨ to 1) to each individual (sub criteria) of each criterion. For the purpose of defuzzification, largest

١٨٩ of maximum method was applied. Based on this method the largest value of the fuzzy subset was

١٩٠ the output value (Mancini et al., 2012).

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2.3. Data gathering

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١٩٣ In order to identify influencing criteria in local seismic amplification the required data were

١٩٤ collected through a literature review and semi-structured interviews with 10 experts who were

١٩٥ involved in the geology, seismology, tectonic, structural engineering, and geomorphology fields.

١٩٦ They were asked about the criteria that can influence local seismic amplification, and then these

١٩٧ data were analyzed using AHP and FL methods as explained in the following:

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2.3.1. Determining the relevant criteria by reviewing literature

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٢٠٠ The potential criteria influencing local seismic amplification susceptibility were determined

٢٠١ through a critical review of literature. By reviewing documents on earthquake engineering,

٢٠٢ seismology, geology, tectonic and structural engineering, geomorphology and seismic

٢٠٣ microzonation reports and guidelines (Fäh et al., 1997;Ding et al., 2004;Molina et al.,

٢٠٤ 2010;Mundepi et al., 2010;Marulanda et al., 2012;Hassanzadeh et al., 2013;Federal Emergency

٢٠٥ Management Agency (FEMA), 2014;Fraume et al., 2014;Grelle et al., 2016;Grelle et al., 2014;SM

٢٠٦ Working Group, 2015;Rehman et al., 2016;Nwe and Tun, 2016;Global Earthquake Model (GEM),

٢٠٧ 2017;CAPRA, 2017;Michel et al., 2017;Trifunac, 2016;Hassanzadeh and Nedovic-Budic, 2016),

٢٠٨ and in total 14 influencing criteria were identified (Table 1).

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

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2.3.2. Experts' Knowledge data

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

٢١٦   The most important criteria were determined by conducting a semi-structured interview with 10

٢١٧   experts using the snowball or chain-referral sampling method (Biernacki and Waldorf, 1981). In

٢١٨   this study, all 10 interviewees were highly experienced and had been involved in seismic

٢١٩   microzonation studies. The average age of the sampled individuals was 43 years, and all of them

٢٢٠   had a postgraduate degree.

٢٢١   A list of criteria that were identified by reviewing previous studies were given to the experts and

٢٢٢   they were requested to add other criteria if they thought they were applicable. They were asked

٢٢٣   to rank each criterion using a five-point Likert Scale (Likert, 1932), so respondents could choose

٢٢٤   the option that best reflected their opinion on each criterion. When surveying many people on

٢٢٥   the same criterion, the five codes could be summed up, averaged or calculate the mode, indicating

٢٢٦   overall positive or negative orientation towards that criterion. This was the basis from which this

٢٢٧   method was used to identify the degree of importance for each criterion in local seismic

٢٢٨   amplification in a region. Therefore, in order to elicit the most relevant criteria, the significance

٢٢٩   of specific factors were measured on a five-point Likert Scale where 1 represents 'not important

٢٣٠   at all', 3 'of little importance', 5 'of average Importance', 7 'very important', and 9 'extremely

٢٣١   important' (Likert, 1932;Jamieson, 2004). The collected data were analysed and criteria with

٢٣٢   mean ratings above '5' ('of average important') were selected (Table 2). These have been then

٢٣٣   considered for further analysis using the Analytic Hierarchy Process (AHP) method.

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

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

٢٣٨   A questionnaire based on AHP matrix (A) was developed for a pair-wise comparison of the

٢٣٩   relative importance of the criteria for calculating the weights (priority ranking) of each criterion.

٢٤٠   As AHP is a subjective method therefore a large sample size is not needed (Cheng and Li,

٢٤١   2002;Lam and Zhao, 1998). For this reason, data were collected by interviewing 10 experts (the

٢٤٢   same experts who were interviewed in the first round) based on the structured questionnaire

٢٤٣ (closed-ended questions). They were asked to compare the relative importance of each criterion

٢٤٤ against all others, based on Saaty's scale by verbal preferences (Saaty, 1980). A pair-wise

٢٤٥ comparison that was carried out with an expert is shown in Table 3. These data are used by the

٢٤٦ AHP method to compute the weight of each criterion as explain previously.

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

٢٤٩ the AHP matrix

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

٢٥٢ In the next step, since each criterion and its sub-criteria has different effect on local seismic

٢٥٣ amplification susceptibility in a region, fuzzy membership functions (MFs) for sub criteria of

٢٥٤ each criterion are defined. As, designed parameters of each membership function depends on

٢٥٥ experts knowledge, then number of memberships, the shape, the positioning, and the overlay area

٢٥٦ of memberships of each MFs for each criterion would be different. To conduct this analysis, 10

٢٥٧ experts were interviewed regarding membership degree of sub criteria of each criterion, and

٢٥٨ mode of each sub criteria was calculated and MFs for each criterion was depicted as described in

٢٥٩ the following:

٢٦٠ - Thickness of soil and sediments: an effective factor in site effect assessment is the thickness of

٢٦١ sediments. Rezaei et al. (2009) stated that the soil thickness demonstrated a positive relationship

٢٦٢ to damage rate observations in the Bam earthquake. This layer was produced by 245 geophysical,

٢٦٣ geotechnical, and sedimentological sampling sites across the city. The alluvial thickness varies in

٢٦٤ different parts of the city. In the northern part of the city, the sediment (marine to continental

٢٦٥ Quaternary deposits including alluvial plain gravels with interlayered clay, silt and sand) thickness

٢٦٦ ranges from 0 m, where bedrock is exposed beneath Arg-e-Bam, to 90 m across most of the

٢٦٧ northern half of the study area. Toward the south and center of the study area, sediment thickness

٢٦٨ increases over a short distance, to more than 270 m. This defines a subsurface of high sediment

٢٦٩ thickness that extends across the entire study area from west to east and underlies south-central

٢٧٠ Bam. Therefore, based on a positive relationship between the damage rate and alluvial thickness

٢٧١ (Rezaei et al., 2009;Marie Nolte, 2010), MF for this criterion is depicted in figure 5a.

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٢٧٣ - Consolidation and strength of soil and sediments: It has been frequently observed that earthquake

٢٧٤ damage is greater in settlements located on unconsolidated and soft soils than in those sited on

٢٧٥ stiff soils or hard rock. For example, in Bam earthquake strong amplification occurred due to the

٢٧٦ extremely soft clay layers that caused high-rise buildings to collapse (Jafari et al., 2005). Another

٢٧٧ example was the Loma Prieta earthquake that happened in 1989, where much of the damage

٢٧٨ occurred in the central San Francisco Bay area at sites underlain by thick deposits of soft clay soils

٢٧٩ (Stewart, 1997). The soil classification has been based on different thresholds for the average shear

٢٨٠ wave velocity (Vs) to a depth of 30m by the National Earthquake Hazard Reduction Program

٢٨١ (NEHRP) to characterize sites for purposes of estimation amplification of seismic motions. This

٢٨٢ standard has applied in Unified Building Code (Dobry et al., 2000) and Eurocode8 (Sabetta and

٢٨٣ Bommer, 2002;Kanlı et al., 2006). Based on this classification in areas on unconsolidated

٢٨٤ sediments, shear wave velocity reduces, and expected amplification during earthquakes could be

٢٨٥ increased. Therefore, according to this MFs for each class have been calculated as shown in figure

٢٨٦ 5b.

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٢٨٨ - Type of soil and particle size distribution of sediments: It has long been recognized that the

٢٨٩ destructiveness of ground shaking during earthquakes can be significantly worsened by the type

٢٩٠ of local soil and subsurface sediment conditions. In past events, the observed variability in seismic

٢٩١ intensity and structural damage severity has often been attributed to the variability of soil and

٢٩٢ subsurface sediment stratigraphy in a given area. Among the geotechnical properties of soil and

٢٩٣ sediments, grain size is one of the most important criteria (Assimaki et al., 2006;Phoon et al.,

٢٩٤ 2006). In the study area, Rezaei et al. (2009) identified eight sediment types: clay, silt, sand,

٢٩٥ granules, pebbles, cobbles, and boulders. They stated that the grain size in the shallow subsurface

٢٩٦ (<10 m) decreases across the city from south to north and increases with depth. Their investigation

٢٩٧ showed that fine-grained soils and sediments (clay, clayey sand, cohesive sandy mud, and cohesive

٢٩٨ muddy sand) dominated the northern part of the city at shallow depths. In the central part of the

٢٩٩ city, fine-grained sediments changed laterally to coarse-grained sediments (poorly sorted sand,

٣٠٠ well-rounded gravel, poorly sorted gravel, and muddy or sandy gravel) which dominated in the

٣٠١ south part of the city. As a rule, it can be assumed that, the smaller the grain size of sediments, the

٣٠٢ less the shear waves velocity and therefore the greater the effect of the seismic wave on the

٣٠٣   destruction level of buildings (Rezaei et al., 2009;Assimaki et al., 2006;Phoon et al., 2006).

٣٠٤   Therefore, the MFs for each specific grain size are calculated in figure 5c.

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٣٠٦   - Depth of groundwater: Research on the effects of groundwater shows it can magnify an

٣٠٧   earthquake's damage. The most well known effect is liquefaction. The geologic and hydrologic

٣٠٨   factors that affect liquefaction susceptibility are the age and the type of sedimentary deposits, the

٣٠٩   looseness of cohesions and the depth to the groundwater table (Tinsley et al., 1985;Cavallaro et

٣١٠   al., 2018). The liquefaction is mostly limited to water-saturated, cohesions less sediments and

٣١١   granular sediments at depths less than 15m (Iguchi and Tainosho, 1998;Sitharam, 2010). Noack

٣١٢   and Fah (2001) categorized it by the depth of the water table, which is split into three classes where

٣١٣   the weight of the class increases while the groundwater table decreases (Fäh et al., 1997).

٣١٤   Therefore, due to the geological conditions in Bam, liquefaction is considered of minor importance

٣١٥   because Talebian et al. (2004) and Rezaei et al. (2009) found water saturated sands in very few

٣١٦   places, however, they reported high amplification in areas that groundwater level was very close

٣١٧   to the ground surface by analyzing microtremore data. Accordingly, MFs for each class of

٣١٨   groundwater depth are computed as shown in figure 5d.

٣١٩   - Type of rock: Type of rocks can effect on local seismic amplification susceptibility in a region.

٣٢٠   Three main types of rock based on their formation process include igneous, metamorphic, and

٣٢١   sedimentary rocks. Each type has its own sub-categories and what matter in this research is how

٣٢٢   hard or soft and how dense the specific type of rocks is in comparison with the other types.

٣٢٣   Geological Strength Index (GSI) of "rock masses depends on rock's material, the amount of joints

٣٢٤   and their relations, alteration, and presence of water" (Hoek and Brown, 1997). There are many

٣٢٥   rock types in the nature that GSI can be calculated for any of them based on their condition, and

٣٢٦   then can be fuzzified addressing their effect on seismic microzonation level of ground shaking.

٣٢٧   There are five classes of GSI including very good, good, fair, poor and very poor based on their

٣٢٨   surface quality and interlocking of rock pieces from massive, blocky, very blocky, disintegrated,

٣٢٩   and laminated/ sheered (Marinos et al., 2007). The GSI values categorized in five classes including

٣٣٠   very low, low, medium, high and very high levels. These classes shows the geological strength of

٣٣١   rocks that the high and very high GSI demonstrate high to very high strength of rocks. Therefore,

٣٣٢   previous studies demonstrates that in massive rocks, high GSI values, seismic waves passes

٣٣٣   quickly and therefore have small influence in seismic microzonation level of ground shaking, and
٣٣٤   vice versa if GSI value gets to the lower values. Thus, in fuzzyfication process of surficial rocks,
٣٣٥   the rock with very high GIS assign 0 and the rocks with very low GSI assign 1 (Figure 6a).
٣٣٦   Furthermore, the criterion of type of bedrock acts the same as surficial rock type criterion as
٣٣٧   explained above. Type of bedrock rarely changed over a small extent with homogenous lithology.
٣٣٨   However, it was concern of experts in determining local seismic amplification susceptibility.

٣٣٩   - Slope: The effects of slope angle on topographic amplification factor was investigated by Bisch
٣٤٠   et al. (2012), and they classified the slope angle into three categories with different effect level
٣٤١   including: 0-15 with no effect, 15-30 degree with 1.2 (coefficient) and more than 30 degree with
٣٤٢   1.4 amplification coefficient. Although, Cavallaro et al. (2012) suggested that topographic
٣٤٣   amplification factor can be considerable for slope even less than 15 degree. Furthermore,
٣٤٤   Bouckovalas and Papadimitriou (2005) investigated the influence of slope topography in
٣٤٥   amplifying the peak horizontal seismic ground acceleration suggesting high amplifications near
٣٤٦   the crest. Grelle et al. (2016) presented formulae for topographic amplification on slope surface.
٣٤٧   These studies indicated that with the increase in slope angle the amplification factor would
٣٤٨   increase. This can be a basis for depicting MFs of this criterion (Figure 6b).

٣٤٩   - Topographic irregularities: Seismic amplification has been witnessed in several earthquakes due
٣٥٠   to topographical changes (Geli et al., 1988;Paolucci, 2002;Cavallaro et al., 2012). Bisch et al.
٣٥١   (2012) classified the site in two classes of "isolated cliff and ridge with crest width significantly
٣٥٢   less than base width" (CEN European Committee for Standardisation, 1994, p 93). However, this
٣٥٣   seems simplistic, as it does not consider the elevation differences. Furthermore, Grelle et al. (2016)
٣٥٤   presented an equation that considered the local slope height, relief height, regional share wave
٣٥٥   velocity and relief ratio. In addition, several calibration constants should be calculated using 2d
٣٥٦   numerical analysis for each study area to compute topographic effects on local seismic
٣٥٧   amplification. Cavallaro et al. (2008) investigated 2d model for analysing site response of the
٣٥٨   Monte Po Hill in the City of Catania considering the effect of topographic and stratigraphic
٣٥٩   properties on the amplification factor in an area. They concluded that near to the slop crest, the
٣٦٠   effect of topographic properties on amplification factor is more relevant than stratigraphic
٣٦١   property. Lee et al. (2009) found out that the amplification on top of elevated surfaces with small
٣٦٢   extent was much higher than valleys and flat areas. Therefore, the elevation differences (dH m)

٣٦٣ 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

٣٦٤ the main driver in computing the amplification coefficient of seismic waves that can effect on local

٣٦٥ seismic amplification susceptibility level of ground. Therefore, the higher the elevation differences

٣٦٦ and the smaller the area of the elevated surface, the ground in this part will be more amplified.

٣٦٧ Here, using fuzzy logic and experts' knowledge the effect of topography in terms of elevation

٣٦٨ differences in determining local seismic amplification susceptibility in the study area is defined

٣٦٩ (Figure 6c).

٣٧٠ Figure 5. Membership functions (MFs) based on fuzzy logic system: Thickness of soil and

٣٧١ sediments (a), Consolidation and strength of soil and sediments (b), Type of soil and particle

٣٧٢ size distribution of sediments (c), Depth of groundwater (d).

٣٧٣

٣٧٤ Figure 6. Membership functions (MFs) based on fuzzy logic system: Type of rock and

٣٧٥ bedrock (a), Slope (degree) (b), Topographic irregularities (c).

٣٧٦

٣٧٧ *2.3.3. Preparing thematic data*

٣٧٨ The required data were collected from relevant organizations and documents and they were

٣٧٩ converted to GIS files in that papered maps were scanned, geo-referenced and then digitized.

٣٨٠ These maps were imported into a geodatabase to validate topological rules and overlaying

٣٨١ condition for all layers. To produce thematic maps, interpolation method such as IDW method

٣٨٢ was applied. The produced maps then were classified based on sub-criteria for each criterion,

٣٨٣ then they were reclassified and converted to raster layers enabling raster combination of all layers

٣٨٤ to each other. These thematic data included: alluvial thickness (Figure 7a), stiffness and strength

٣٨٥ of soil and sediments (Figure 7b), type of soil and particle size distribution of soil and sediments

٣٨٦ (Figure 8a and b), depth of groundwater (Figure 9a), type of rock (Figure 9b), topographic

٣٨٧ irregularities (Figure 10a), and slope (Figure 10b) layers.

٣٨٨

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

٣٩٠ and sediments (b).

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

392   meters (b).

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

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

395

2.3.4. Preparing control data

397   National Cartographic Center (2003) and Hisada et al.(2005) were collected data on the destruction

398   level of buildings after math of the Bam earthquake (Figure 11a and b). Lashkari Pour et al. (2006)

399   and Motamed et al. (2007) were collected data on the dominant frequency of soil (Figure 12a and

400   b) and amplification factor by Motamed et al. (2007) (Figure 13) using microtremor measurements

401   in Bam city. These datasets were classified to 5 classes based on equal interval classification

402   method including very low, low, moderate, high and very high classes. Then, they were applied to

403   validate the model's output through a comparison analysis and calculating overall accuracy and

404   kappa coefficient.

405

406   Figure 11. Control data: Actual building destruction level (Hisada et al., 2005) (a), percentage of

407   damage to buildings caused by the Bam earthquake in 2003 (National Cartographic Center of

408   Iran (NCCI), 2003) (b).

409

410   Figure 12. Control data: Dominant frequency by (LashkariPour et al., 2006) (a) and by Motamed

411   et al. (2007) (b) using Microtremor field measurement.

412

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

414   measurement.

415

2.3. Spatial combination methods and overlay rules

417   The spatial Multi Criteria Decision Making (MCDM) approach is a decision-aid and a

418   mathematical tool that combines and transforms spatially referenced data into a raster layer with

419 a priority score. (Roy, 1996;Malczewski, 2006). Several combination methods have been

420 developed, such as Boolean operations (Malczewski, 1999), weighted linear combination (WLC:

421 combining the normalized criteria based on overlay analysis) (Voogd, 1983;Drobne and Lisec,

422 2009;O'Sullivan and Unwin, 2010) (Eq. 5), ordered weighted averaging (OWA) (Yager,

423 1988;Rinner and Malczewski, 2002), and Analytical Hierarchy Process (AHP) based on the

424 additive weighting methods (Zhu and Dale, 2001). In this research, the AHP method (Saaty,

425 1980) was used to derive the weights associated with criteria and Fuzzy Logic method was

426 applied to compute sub-criteria's membership functions (MFs) in order to produce the local

427 seismic amplification. Then, the degree of membership of each sub-criteria (calculated by Fuzzy

428 Logic method) is assigned to the corresponding sub-criteria. Next, this is multiplied by the weight

429 of corresponding criteria (calculated by AHP method). Finally, they are summed up in a linear

430 manner using WLC method (Eq. 5) to develop the model (Larzesh model) for production of the

431 local seismic amplification in the study area.

$$Ai = \sum W_j * X_{ij} \hspace{4cm} (Eq.\ 5)$$

432 *Where: w_j = the calculated weight of criteria j, and Xij = the degree of memebrship of the ith*

433 *sub-criteria with respect to the jth criteria, and Ai = the local seismic amplification index in ith*

434 *location.*

435

2.4. Validation and comparison methods

436

437 In order to validate the model, as categorical variables are the main driver of model development in

438 this research, therefore relevant measures such as Overall Accuracy and Kappa statistic will be

439 applied to measure the performance of the model.

440 *a) Overall accuracy (OA)*

441 Accuracy assessments determine the quality of the results derived from data analysis or a model,

442 in comparison with a reference or ground truth data (where ground truth data are assumed to be

443 100% correct) (Congalton and Green, 2009). The accuracy assessment can be obtained by

444 creating a contingency table of counts of observations, with calculated, estimated or predicted

445 data values as rows and with reference data values as columns. The values in the shaded cells

446 along the diagonal represent counts for correctly classified observations, where the reference data

٤٤٧   matches the predicted value. This contingency table is often referred to as a confusion matrix,

٤٤٨   misclassification matrix, or error matrix (Czaplewski, 1992;Congalton and Green, 2009) (Eq. 6).

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

٤٤٩

٤٥٠   *Where: OA = Overal Accuracy, n_{kk} = Values in diagonal cell of the matrix (correctly classified*

٤٥١   *observations), and n = number of observations.*

٤٥٢   *b) Kappa analysis*

٤٥٣   The kappa statistic (κ) (Sim and Wright, 2005;Congalton and Green, 2008) calculates degree of

٤٥٤   agreement between classes of two independent observe measuring the same property. The degree

٤٥٥   of Kappa would be 0 for a random classifies and 1 for classification. Degree of agreement of

٤٥٦   Kappa interprets as follows: less than 0.4: poor agreement, 0.4 and 0.8: moderate agreement,

٤٥٧   and greater than 0.80: strong agreement (Congalton and Green, 2008) (Eq. 7).

٤٥٨

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

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

٤٦١   *agreement.*

٤٦٢

٤٦٣   **Results and discussion**

٤٦٤   In order to produce the local seismic amplification susceptibility the most important criteria were

٤٦٥   identified and then were weighted using AHP pair-wise comparison method. The higher weight

٤٦٦   belong to alluvial thickness (0.271), stiffness and strength of soil and sediments (0.207), type of

٤٦٧   soil and particle size distribution of sediments (0.177), depth of groundwater (0.171), topographic

٤٦٨   irrigularities (0.054), type of rock (0.041), slope (0.040), and type of bedrock (0.040) were

٤٦٩   considered. Then, based on Fuzzy Logic method sub-criteria of each criterion was fuzzified and

٤٧٠   membership functions for them was defined. Next, these criteria were combined based on the

٤٧١   Weighted Linear Combination (WLC) (Drobne and Lisec, 2009) in GIS to develop the model for

٤٧٢ producing the susceptibility map of local seismic amplification for the study area, as it is proposed

٤٧٣ in the following (Eq. 8):

٤٧٤

٤٧٥ $$A_j = \sum(wS_s . FS_{ss}) + (wT_A . FS_{TA}) + (wS_A . FS_{SA}) + (wD_{Gw} . FS_{DGW}) + (wT_R . FS_{TR})$$

٤٧٦ $$+ (wT_{Br} . FS_{TBR}) + (wT_S . FS_{TS}) + (wS_L . FS_{SL}) \qquad (Eq. 8)$$

٤٧٧ *Where: A_j = local seismic amplification susceptibility, weights of each criterion: wS_s = stiffness and*

٤٧٨ *strength of soil and sediments , wT_A = Alluvial thickness, wS_A = Type of soil and particle size distribution*

٤٧٩ *of sediments , wD_{Gw} = depth of groundwater , wT_R = type of rock , wT_{Br} = type of bedrock, wT_S =*

٤٨٠ *topographic irregularities, wS_L = slope, and fuzzified sub-criteria of each criterion: FS_{ss} = stiffness and*

٤٨١ *strength of soil and sediments, FS_{TA} = Alluvial thickness, FS_{SA} = Type of soil and particle size distribution*

٤٨٢ *of soil and sediments, FS_{DGW} = depth of groundwater, FS_{TR} = type of rock , FS_{TBR} = type of bedrock,*

٤٨٣ *FS_{TS} = topographic irregularities, and FS_{SL} = slope.*

٤٨٤

٤٨٥ Figure 14 displays the resulting microzonation map of ground shaking in Bam city. The areas

٤٨٦ with high to very high susceptibility to local seismic amplification are located in the north, east

٤٨٧ and northeast part of Bam city. This is due to the widespread unconsolidated sediments, low

٤٨٨ groundwater level in combination with high sediment thickness.

٤٨٩ In order to validate the results, OA and Kappa methods were applied comparing the output of

٤٩٠ model with the measured predominant frequency (Askari et al., 2004;LashkariPour et al.,

٤٩١ 2006;Motamed et al., 2007) in the study area. The results demonstrated 73.6% and 82% (Table

٤٩٢ 4a and b) for OA and 0.74 and 0.75 for Kappa (Table 5) indicating a good fit of the model's

٤٩٣ output with the measured data. Moreover, the overlay of the building destructions caused by the

٤٩٤ Bam earthquake in 2003 (Hisada et al., 2005;National Cartographic Center of Iran (NCCI), 2003)

٤٩٥ shows that high destruction levels happened in locations with high ground shaking which were

٤٩٦ located in central, north and northeast part of the city.

٤٩٧

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

٤٩٩

٥٠٠ Table 4. Comparison between the model's output with the measured predominant frequanecy in Bam

٥٠١ city by Motamed et al. (2007) (a)c and LashkariPour et al. (2006) (b).

٥٠٣   Table 5. Kappa coefficient and OA

٥٠٤

٥٠٥   In this study, we have focused on the site effect and local geology properties of a site that have a

٥٠٦   massive influence on local seismic amplification susceptibility in the study area. To deal with

٥٠٧   related uncertainties in preparing seismic microzonation, the most important criteria were selected,

٥٠٨   weighted and then fuzzified. Criteria with high uncertainty degree such as distance of active fault

٥٠٩   to the site, depth and magnitude of the probable earthquake were not considered because there was

٥١٠   no possibility to exactly find out where and how an earthquake will be triggered. Therefore, only

٥١١   the criteria with known location (x and y) and known characteristics were taken into consideration.

٥١٢   Furthermore, to deal with uncertainties Fuzzy Logic is a suitable approach as we can define

٥١٣   membership function of the effect of each criterion in the amplification of ground shaking by

٥١٤   interviewing 10 experts and obtaining expert's knowledge. This can result in realistic output

٥١٥   regarding the behavior of each criterion in ground shaking calculation.

٥١٦   The newly developed model uses AHP and Fuzzy Logic (Zadeh, 1965) to deal with complexities

٥١٧   and uncertainties in data analyses in weighting the criteria and fuzzifying the sub-criteria of each

٥١٨   criterion. Although, in studies for evaluating seismic microzonation in Bangalore (India) (Sitharam

٥١٩   and Anbazhagan, 2008), Dehli (Mohanty et al., 2007), Haldia (India) (Mohanty et al., 2007), Erbaa

٥٢٠   (Turkey) (Akin et al., 2013) and Al-Madinah (Moustafa et al., 2016) only AHP method was applied

٥٢١   to weight the criteria, and none of these studies considered weighting of sub criteria for each

٥٢٢   criterion even using other methods.

٥٢٣   Few researchers have considered direct properties of influencing factors in assessing ground

٥٢٤   shaking amplification. Even, in evaluating seismic response developed models such as

٥٢٥   SiSeRHMap v1.0 (Grelle et al., 2016) and GIS Cubic Model (Grelle et al., 2014), the researchers

٥٢٦   have applied only lithodynamic, stratigraphic and topographic effects as influencing factors.

٥٢٧   Furthermore, Aucelli et al. (2018) suggested a method for producing susceptibility index to local

٥٢٨   seismic amplification in Isernia Province, Italy, and they have considered geological and

٥٢٩   geomorphological properties of studied areas. Although, they have not considered the use of multi-

٥٣٠   criteria decision-making methods (MCDM) in weighting and combining the influencing criteria

٥٣١   which is the aim of current study. The current research considers direct properties of each criteria

٥٣٢   and tries to manage uncertainties in criteria and sub-criteria of each criterion via weighting and

533 fuzzification process using experts' knowledge and the use of direct properties of criteria. These

534 processes can be extended in more details, which are subject to more investigation in the future.

535

Conclusions

537 Larzesh model introduces a new method based on AHP and Fuzzy Logic rules that enables experts

538 to produce local seismic amplification susceptibility using direct properties of lithological,

539 sedimentological, geological, hydrological and topographical effects in a study area using experts'

540 knowledge in weighting and fuzzifing criteria and sub criteria that can be readily perceived and

541 consulted.

542 The application of the model was carried out in the urban area of the Bam city in Iran. The results

543 demonstrated high to very high ground shaking amplifications were located in central, east, and

544 northeast to north part of the city that was confirmed comparing with measured microtremor data

545 on predominate frequency in the study area. However, as the proposed model is a spatial

546 computational tool, the validation of output in producing local seismic amplification strictly

547 dependent on the quality and preparation of input data.

548 In conclusion, the model enable disaster managers, planners, and policy makers in producing local

549 seismic amplification susceptibility and making informed decision in urban planning and

550 designing appropriate plans for urban development, especially in areas with high seismic activities.

551

Acknowledgements

553 The authors would like to express their appreciation to Institute of Science and High Technology

554 and Environmental Sciences, Graduate University of Advanced Technology, Kerman, Iran for

555 financial support of this study under reference number of 7/C/95/2053.

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References

558 Akin, M. K., Topal, T., and Kramer, S. L.: A newly developed seismic microzonation model of Erbaa
559 (Tokat, Turkey) located on seismically active eastern segment of the North Anatolian Fault Zone (NAFZ),
560 Natural Hazards, 65, 1411-1442, 10.1007/s11069-012-0420-1, 2013.

561 Askari, F., Azadi, A., M., D., and M.R. Ghayamghamian, E. H., H. Hamzehloo, M.K. Jafari, M. Kamalian,
562 M. Keshavarz, O. Ravanfar, A. Shafiee, A. Sohrabi-Bidar: Preliminary Seismic Microzonation of Bam,
563 Journal of Seismology and Earthquake Engineering, 5, 2004.

Assimaki, D., Steidl, J., and Liu, P.: Attenuation and Velocity Structure for Site Response Analyses via Downhole Seismogram Inversion, Pure appl. geophys., 163, 81-118, 10.1007/s00024-005-0009-7, 2006.

Atkinson, G. M., and Boore, D. M.: Earthquake ground-motion prediction equations for eastern North America, Bulletin of the Seismological Society of America, 96, 2181-2205, 2006.

Atkinson, G. M., Ghofrani, H., and Assatourians, K.: Impact of induced seismicity on the evaluation of seismic hazard: Some preliminary considerations, Seismological Research Letters, 86, 1009-1021, 2015.

Aucelli, P. P. C., Di Paola, G., Valente, E., Amato, V., Bracone, V., Cesarano, M., Di Capua, G., Scorpio, V., Capalbo, A., and Pappone, G.: First assessment of the local seismic amplification susceptibility of the Isernia Province (Molise Region, Southern Italy) by the integration of geological and geomorphological studies related to the first level seismic microzonation project, Environmental earth sciences, 77, 118, 2018.

Beck, J. L., and Hall, J. F.: Factors contributing to the catastrophe in Mexico City during the earthquake of September 19, 1985, Geophysical Research Letters, 13, 593-596, 1986.

Biernacki, P., and Waldorf, D.: Snowball sampling: Problems and techniques of chain referral sampling, Sociological methods & research, 10, 141-163, 1981.

Bisch, P., Carvalho, E., Degee, H., Fajfar, P., Fardis, M., Franchin, P., Kreslin, M., Pecker, A., Pinto, P., and Plumier, A.: Eurocode 8: seismic design of buildings worked examples, Joint Research Centre European Union, Luxembourg, 2012.

Boore, D. M.: Simulation of ground motion using the stochastic method, in: Seismic Motion, Lithospheric Structures, Earthquake and Volcanic Sources: The Keiiti Aki Volume, Springer, 635-676, 2003.

Boostan, E., Tahernia, N., and Shafiee, A.: Fuzzy—probabilistic seismic hazard assessment, case study: Tehran region, Iran, Natural Hazards, 77, 525-541, 2015.

Bouckovalas, G. D., and Papadimitriou, A. G.: Numerical evaluation of slope topography effects on seismic ground motion, Soil Dynamics and Earthquake Engineering, 25, 547-558, 2005.

Campbell, K. W.: Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America, Bulletin of the Seismological Society of America, 93, 1012-1033, 2003.

Capilleri, P., Cavallaro, A., and Maugeri, M.: Static and dynamic soil characterization at Roio Piano (AQ), Italian Geotechnical Journal, 35, 2, 2014.

Probabilistic Risk Assessment (CAPRA): https://www.ecapra.org/software, access: 17 April 2017, 2017.

Castelli, F., Cavallaro, A., Grasso, S., and Lentini, V.: Seismic microzoning from synthetic ground motion earthquake scenarios parameters: the case study of the City of Catania (Italy), Soil Dynamics and Earthquake Engineering, 88, 307-327, 2016a.

Castelli, F., Cavallaro, A., Grasso, S., and Ferraro, A.: In situ and laboratory tests for site response analysis in the ancient city of Noto (Italy), Proceedings of the 1st IMEKO TC4 International Workshop on Metrology for Geotechnics, Benevento, Italy, 2016b, 17-18,

٥٩٩ Cavallaro, A., Ferraro, A., Grasso, S., and Maugeri, M.: Site response analysis of the Monte Po Hill in the
٦٠٠ City of Catania, AIP Conference Proceedings, 2008, 240-251,

٦٠١ Cavallaro, A., Ferraro, A., Grasso, S., and Maugeri, M.: Topographic effects on the Monte Po hill in Catania
٦٠٢ (Italy), Soil Dynamics and Earthquake Engineering, 43, 97-113, 2012.

٦٠٣ Cavallaro, A., Capilleri, P., and Grasso, S.: Site characterization by dynamic in situ and laboratory tests for
٦٠٤ liquefaction potential evaluation during Emilia Romagna earthquake, Geosciences, 8, 242, 2018.

٦٠٥ CEN European Committee for Standardisation: Eurocode 8. Design Provisions for Earthquake Resistance
٦٠٦ of Structures—Part 5: Foundations, Retaining Structures and Geotechnical Aspects. ENV 1998-5, Brussels,
٦٠٧ 1994.

٦٠٨ Cheng, E. W. L., and Li, H.: Construction partnering process and associated critical success factors:
٦٠٩ quantitative investigation, Journal of Management in Engineering, October, 194–202, 2002.

٦١٠ Congalton, R. G., and Green, K.: Assessing the accuracy of remotely sensed data: principles and practices,
٦١١ CRC press, 2008.

٦١٢ Congalton, R. G., and Green, K.: Assessing the Accuracy of Remotely Sensed Data: Principles and
٦١٣ Practices, CRC Press, Boca Raton, FL, USA, 2009.

٦١٤ Cornell, C. A.: Engineering seismic risk analysis, Bulletin of the seismological society of America, 58,
٦١٥ 1583-1606, 1968.

٦١٦ Czaplewski, R. L.: Misclassification bias in areal estimates, Photogrammetric engineering and Remote
٦١٧ Sensing, 58, 189–192, 1992.

٦١٨ Demicco, R. V., and Klir, G. J.: Fuzzy logic in geology, Academic Press, 347 pp., 2003.

٦١٩ Ding, Z., Chen, Y., and Panza, G.: Estimation of site effects in Beijing City, Pure appl. geophys., 161, 1107-
٦٢٠ 1123, 2004.

٦٢١ Dobry, R., Borcherdt, R. D., Crouse, C. B., Idriss, I. M., Joyner, W. B., Martin, G. R., Power, M. S., Rinne,
٦٢٢ E. E., and Seed, R. B.: New site coefficients and site classification system used in recent building seismic
٦٢٣ code provisions, Earthquake Spectra, 16, 41-67, 2000.

٦٢٤ Drobne, S., and Lisec, A.: Multi-attribute Decision Analysis in GIS: Weighted Linear Combination and
٦٢٥ Ordered Weighted Averaging, Informatica (Slovenia), 33, 459-474, 2009.

٦٢٦ Fäh, D., Rüttener, E., Noack, T., and Kruspan, P.: Microzonation of the city of Basel, Journal of
٦٢٧ Seismology, 1, 87-102, 10.1023/a:1009774423900, 1997.

٦٢٨ Federal Emergency Management Agency (FEMA): Multi-hazard Loss Estimation Methodology,
٦٢٩ Earthquake Model, HAZUS®MH MR5, User Manual, Washington, D.C., 2014.

٦٣٠ Figueira, J., Mousseau, V., and Roy, B.: ELECTRE methods, in: Multiple criteria decision analysis: State
٦٣١ of the art surveys, Springer, 133-153, 2005.

٦٣٢ Fraume, M., Cristina, M., Carreño Tibaduiza, M. L., Cardona Arboleda, O. D., Ordaz Schroeder, M. G.,
٦٣٣ and Barbat Barbat, H. A.: Probabilistic earthquake risk assessment of Barcelona using CAPRA, Second
٦٣٤ European Conference on Earthquake Engineering and Seismology, 2014, 1-3,

٦٣٥ Geli, L., Bard, P.-Y., and Jullien, B.: The effect of topography on earthquake ground motion: a review and
٦٣٦ new results, Bulletin of the Seismological Society of America, 78, 42-63, 1988.

٦٣٧ Geological Survey of Iran: Geological Map of Iran, 1:100,000 Series, Sheet 7648, Bam, Iran, 1993.

٦٣٨ Global Earthquake Model (GEM): The OpenQuake-engine User Manual. Global Earthquake Model (GEM)
٦٣٩ Technical Report 2017-02., 193 2017.

٦٤٠ Grelle, G., Bonito, L., Revellino, P., Guerriero, L., and Guadagno, F. M.: A hybrid model for mapping
٦٤١ simplified seismic response via a GIS-metamodel approach, Natural Hazards and Earth System Sciences,
٦٤٢ 14, 1703, 2014.

٦٤٣ Grelle, G., Bonito, L., Lampasi, A., Revellino, P., Guerriero, L., Sappa, G., and Guadagno, F. M.:
٦٤٤ SiSeRHMap v1. 0: a simulator for mapped seismic response using a hybrid model, Geoscientific Model
٦٤٥ Development, 9, 1567-1596, 2016.

٦٤٦ Hassanzadeh, R., Nedović- Budić, Z., Alavi Razavi, A., Norouzzadeh, M., and Hodhodkian, H.: Interactive
٦٤٧ approach for GIS-based earthquake scenario development and resource estimation (Karmania hazard
٦٤٨ model), The international jounal of Computers & Geosciences, 51, 324-338, 10.1016/j.cageo.2012.08.016,
٦٤٩ 2013.

٦٥٠ Hassanzadeh, R., and Nedovic-Budic, Z.: Where to go first: prioritization of damaged areas for allocation
٦٥١ of Urban Search and Rescue (USAR) operations (PI-USAR model), Geomatics, Natural Hazards and Risk,
٦٥٢ 7, 1337-1366, 10.1080/19475705.2015.1058861, 2016.

٦٥٣ Hinlopen, E., Nijkamp, P., and Rietveld, P.: Qualitative discrete multiple criteria choice models in regional
٦٥٤ planning, Regional Science and Urban Economics, 13, 77-102, 1983.

٦٥٥ Hisada, Y., Shibayama, A., and Ghayamghamian, M. R.: Building damage and seismic intensity in Bam
٦٥٦ city from the 2003 Iran, Bam, earthquake, Bull. Earthquake Res. Inst., Univ. Tokyo, 79 81–94, 2005.

٦٥٧ Hoek, E., and Brown, E. T.: Practical estimates of rock mass strength, International Journal of Rock
٦٥٨ Mechanics and Mining Sciences, 34, 1165-1186, 1997.

٦٥٩ Iguchi, Y., and Tainosho, Y.: Characteristics of distribution of groundwater level in the seismic damaged
٦٦٠ zone in eastern part of Kobe city due to the 1995 Hyogo-Ken Nanbu Earthquake, Bulletin of the Faculty of
٦٦١ Human Development 5, 403-415, 1998.

٦٦٢ Jafari, M. K., Ghayamghamian, M. R., Davoodi, M., Kamalian, M., and Sohrabi-Bidar, A.: Site Effects of
٦٦٣ the 2003 Bam, Iran, Earthquake, Earthquake Spectra, 21, 125-136, 10.1193/1.2098266, 2005.

٦٦٤ Jamieson, S.: Likert Scales: How to (Ab)use Them, Medical Education, 38, 1217-1218, 2004.

٦٦٥ Kanlı, A. I., Tildy, P., Prónay, Z., Pınar, A., and Hermann, L.: VS30 mapping and soil classification for
٦٦٦ seismic site effect evaluation in Dinar region, SW Turkey, Geophysical Journal International, 165, 223-
٦٦٧ 235, 10.1111/j.1365-246X.2006.02882.x, 2006.

٦٦٨ Keeney, R. L., and Raiffa, H.: Decisions with multiple objectives: preferences and value trade-offs,
٦٦٩ Cambridge university press, 1993.

٦٧٠ Klir, G. J.: Chapter 2 - Fuzzy Logic: A Specialized Tutorial, in: Fuzzy Logic in Geology, Academic Press,
٦٧١ Burlington, 11-61, 2004.

٦٧٢ Lam, K., and Zhao, X.: An application of quality function deployment to improve the quality of teaching,
٦٧٣ International Journal of Quality Reliability Management, 15, 389–413, 1998.

٦٧٤ LashkariPour, G. R., Sadegh, H., and Sevizi, Z.: Comparison of predominant frequency of Bam city using
٦٧٥ seismic facies and ratio of H/V of foreshocks earthquakes., 10th Symposium of Geological Society of Iran,
٦٧٦ 2006.

٦٧٧ Lee, S.-J., Komatitsch, D., Huang, B.-S., and Tromp, J.: Effects of topography on seismic-wave
٦٧٨ propagation: An example from northern Taiwan, Bulletin of the Seismological Society of America, 99,
٦٧٩ 314-325, 2009.

٦٨٠ Likert, R.: A Technique for the Measurement of Attitudes, Archives of Psychology, 140, 1932.

٦٨١ Malczewski, J.: GIS and Multicriteria Decision Analysis, John Wiley and Sons, New York, 1999.

٦٨٢ Malczewski, J.: A GIS-based multicriteria decision analysis: A survey of the literature, International Journal
٦٨٣ of Geographical Information Science, 20, 703-726, 2006.

٦٨٤ Mancini, I. M., Masi, S., Caniani, D., and Lioi, D. S.: Fuzzy logic and neuro-fuzzy networks for
٦٨٥ environmental hazard assessment, in: Fuzzy Logic-Emerging Technologies and Applications, InTech,
٦٨٦ 2012.

٦٨٧ Marie Nolte, E.: Earthquake risk map development using GIS and optical satellite imagery: case study for
٦٨٨ rural areas on Java, Indonesia, Center for Disaster Management and Risk Reduction Technology
٦٨٩ Projektbericht Hertz, Karlsruhe 112, 2010.

٦٩٠ Marinos, P., Marinos, V., and Hoek, E.: Geological Strength Index (GSI). A characterization tool for
٦٩١ assessing engineering properties for rock masses, Underground works under special conditions. Taylor and
٦٩٢ Francis, Lisbon, 13-21, 2007.

٦٩٣ Marulanda, M., Carreño, M., Cardona, O., and Barbat, A.: Probabilistic assessment of seismic risk of
٦٩٤ Barcelona, Spain, using the CAPRA platform, Buletinul Institutului Politehnic din Iasi. Sectia Constructii,
٦٩٥ Arhitectura, 58, 9, 2012.

٦٩٦ MERM: Microzonation Manual, World Institute for Disaster Risk Management, 2003.

٦٩٧ Michel, C., Fäh, D., Edwards, B., and Cauzzi, C.: Site amplification at the city scale in Basel (Switzerland)
٦٩٨ from geophysical site characterization and spectral modelling of recorded earthquakes, Physics and
٦٩٩ Chemistry of the Earth, Parts A/B/C, 98, 27-40, 2017.

٧٠٠ Mohanty, W. K., Walling, M. Y., Nath, S. K., and Pal, I.: First Order Seismic Microzonation of Delhi, India
٧٠١ Using Geographic Information System (GIS), Natural Hazards, 40, 245-260, 10.1007/s11069-006-0011-0,
٧٠٢ 2007.

٧٠٣ Mohanty, W. K., and Walling, M. Y.: First Order Seismic Microzonation of Haldia, Bengal Basin (India)
٧٠٤ Using a GIS Platform, Pure appl. geophys., 165, 1325-1350, 10.1007/s00024-008-0360-6, 2008.

٧٠٥ Molina, S., Lang, D. H., and Lindholm, C. D.: SELENA – An open-source tool for seismic risk and loss
٧٠٦ assessment using a logic tree computation procedure, Computers & Geosciences, 36, 257-269,
٧٠٧ http://dx.doi.org/10.1016/j.cageo.2009.07.006, 2010.

٧٠٨ Monaco, P., Totani, G., Barla, G., Cavallaro, A., Costanzo, A., d'Onofrio, A., Evangelista, L., Foti, S.,
٧٠٩ Grasso, S., and Lanzo, G.: Geotechnical aspects of the L'Aquila earthquake, in: Special topics in earthquake
٧١٠ geotechnical engineering, Springer, 1-66, 2012.

٧١١ Moro, M., Saroli, M., Salvi, S., Stramondo, S., and Doumaz, F.: The relationship between seismic
٧١٢ deformation and deep-seated gravitational movements during the 1997 Umbria–Marche (Central Italy)
٧١٣ earthquakes, Geomorphology, 89, 297-307, 2007.

٧١٤ Motamed, R., Ghalandarzadeh, A., Tawhata, I., and Tabatabaei, S. H.: Seismic Microzonation and Damage
٧١٥ Assessment of Bam City, Southeastern Iran, Journal of Earthquake Engineering, 11, 110-132,
٧١٦ 10.1080/13632460601123164, 2007.

٧١٧ Moustafa, S. S. R., SN Al-Arifi, N., Jafri, M. K., Naeem, M., Alawadi, E. A., and A. Metwaly, M.: First
٧١٨ level seismic microzonation map of Al-Madinah province, western Saudi Arabia using the geographic
٧١٩ information system approach, Environmental Earth Sciences, 75, 251, 10.1007/s12665-015-5073-4, 2016.

٧٢٠ Mundepi, A., Galiana-Merino, J., and Lindholm, C.: Soil characteristics and site effect assessment in the
٧٢١ city of Delhi (India) using H/V and f–k methods, Soil Dynamics and Earthquake Engineering, 30, 591-599,
٧٢٢ 2010.

٧٢٣ Nath, S., and Thingbaijam, K.: Seismic hazard assessment-a holistic microzonation approach, Natural
٧٢٤ Hazards and Earth System Sciences, 9, 1445, 2009.

٧٢٥ National Cartographic Center of Iran (NCCI): Report on the Bam earthquake, Tehran, 98, 2003.

٧٢٦ Noack, T., and Fah, D.: Earthquake Microzonation: site effects and local geology; A case study for the
٧٢٧ Kanton of Basel-Stadt, 2001.

٧٢٨ Novák, V., Perfilieva, I., and Mockor, J.: Mathematical principles of fuzzy logic, Springer Science &
٧٢٩ Business Media, 2012.

٧٣٠ Nwe, Z. Z., and Tun, K. T.: Seismic Hazard Analysis using AHP-GIS, Int'l Journal of Research in Chemical,
٧٣١ Metallurgical and Civil Engg., 3, 1442-1450, 2016.

٧٣٢ O'Sullivan, D., and Unwin, D. J.: Putting Maps Together—Map Overlay, in: Geographic Information
٧٣٣ Analysis, John Wiley & Sons, Inc., 315-340, 2010.

٧٣٤ Panza, G. F., La Mura, C., Peresan, A., Romanelli, F., and Vaccari, F.: Chapter three-seismic hazard
٧٣٥ scenarios as preventive tools for a disaster resilient society, Advances in geophysics, 53, 93-165, 2012.

٧٣٦ Paolucci, R.: Amplification of earthquake ground motion by steep topographic irregularities, Earthquake
٧٣٧ Engineering & Structural Dynamics, 31, 1831-1853, 10.1002/eqe.192, 2002.

٧٣٨ Petersen, M. D., Mueller, C. S., Moschetti, M. P., Hoover, S. M., Llenos, A. L., Ellsworth, W. L., Michael,
٧٣٩ A. J., Rubinstein, J. L., McGarr, A. F., and Rukstales, K. S.: Seismic-Hazard Forecast for 2016 Including
٧٤٠ Induced and Natural Earthquakes in the Central and Eastern United States, Seismological Research Letters,
٧٤١ 87, 1327-1341, 2016.

742   Phoon, K., Nadim, F., Uzielli, M., and Lacasse, S.: Soil variability analysis for geotechnical practice, in:
743   Characterisation and Engineering Properties of Natural Soils, Taylor & Francis, 2006.

744   Ramazi, H., and Jigheh, H. S.: The Bam (Iran) Earthquake of December 26, 2003: From an engineering
745   and seismological point of view, Journal of Asian Earth Sciences, 27, 576-584, 2006.

746   Rehman, F., El-Hady, S. M., Atef, A., and Harbi, H. M.: PROBABILISTIC SEISMIC HAZARD
747   ASSESSMENT METHODOLOGY AND SITE RESPONSE ANALYSIS APPLICATION TO SEISMIC
748   MICROZONATION, Science International, 28, 2016.

749   Rezaei, K., Guest, B., Friedrich, A., Fayazi, F., Nakhaei, M., Beitollahi, A., and Fatemi Aghda, S.: Feed
750   forward neural network and interpolation function models to predict the soil and subsurface sediments
751   distribution in Bam, Iran, Acta Geophys., 57, 271-293, 10.2478/s11600-008-0073-3, 2009.

752   Rinner, C., and Malczewski, J.: Web-enabled spatial decision analysis using ordered weighted averaging,
753   J Geogr Syst, 4, 385–403, 2002.

754   Roy, B.: Multicriteria methodology for decision aiding, Kluwer Academic Publishers, Dordrecht, 1996.

755   Saaty, T. L.: The Analytic Hierarchy Process: planning, priority setting, resource allocation, McGraw-Hill
756   International, US, 1980.

757   Saaty, T. L.: An Exposition of the AHP in Reply to the Paper "Remarks on the Analytic Hierarchy Process",
758   Management Science, 36, 259-268, 10.1287/mnsc.36.3.259, 1990.

759   Sabetta, F., and Bommer, J.: Modification of the spectral shapes and subsoil conditions in Eurocode 8, 12th
760   European Conference on Earthquake Engineering, London, UK, 2002.

761   Sen, Z.: Rapid visual earthquake hazard evaluation of existing buildings by fuzzy logic modeling, Expert
762   Systems with Applications, 37, 5653-5660, 2010.

763   Sim, J., and Wright, C. C.: The kappa statistic in reliability studies: use, interpretation, and sample size
764   requirements, Physical therapy, 85, 257-268, 2005.

765   Sitharam, T., and Anbazhagan, P.: Seismic microzonation: principles, practices and experiments, EJGE
766   Special Volume Bouquet, 8, 2008.

767   Sitharam, T. G.: Technical Documat on Geotechnical and Geophysical Investigation for Seismic
768   Microzonation Studies of Urban Centers in India, National Disaster Management Authority (NDMA),
769   Bhawan, Safdarjung Enclave, New Delhi, 123, 2010.

770   SM Working Group: Guidelines for Seismic Microzonation, Civil Protection Department and Conference
771   of Regions and Autonomous Provinces of Italy, 2015,

772   Stewart, J.: Key Geotechnical Aspects of the 1989 Loma Prieta Earthquake, National Information Service
773   for Earthquake Engineering, University of California, Berkeley, California, Berkeley, 1997.

774   Talebian, M., Fielding, E. J., Funning, G. J., Ghorashi, M., Jackson, J., Nazari, H., Parsons, B., Priestley,
775   K., Rosen, P. A., Walker, R., and Wright, T. J.: The 2003 Bam (Iran) earthquake: Rupture of a blind strike-
776   slip fault, Geophysical Research Letters, 31, n/a-n/a, 10.1029/2004gl020058, 2004.

٧٧٧ Tang, A. K.: Izmit (Kocaeli), Turkey, Earthquake of August 17, 1999 Including Duzce Earthquake of
٧٧٨ November 12, 1999: Lifeline Performance, ASCE Publications, 2000.

٧٧٩ Teramo, A., Termini, D., Marullo, A., and Marino, A.: Fuzzy interpolators for a quick seismic
٧٨٠ microzonation, CIMSA. 2005 IEEE International Conference on Computational Intelligence for
٧٨١ Measurement Systems and Applications, 2005., 2005, 107-108,

٧٨٢ Tinsley, J. C., Youd, T. L., D.M., P., and Chen, A. T. F.: Evaluating liquefaction potential. In: Evaluating
٧٨٣ Earthquake Hazards in the Los Angeles Region - An Earth-Science Perspective, US Geological Survey,
٧٨٤ 263-315, 1985.

٧٨٥ Trifunac, M. D.: Site conditions and earthquake ground motion – A review, Soil Dynamics and Earthquake
٧٨٦ Engineering, 90, 88-100, https://doi.org/10.1016/j.soildyn.2016.08.003, 2016.

٧٨٧ Voogd, H.: Multicriteria Evaluation for Urban and Regional Planning, Pion, Ltd, London, 1983.

٧٨٨ Wald, D. J.: Slip history of the 1995 Kobe, Japan, earthquake determined from strong motion, teleseismic,
٧٨٩ and geodetic data, Journal of Physics of the Earth, 44, 489-503, 1996.

٧٩٠ Wang, Z., Carpenter, N. S., and Zhang, L.: Assessing Potential Seismic Hazards from Induced Earthquakes
٧٩١ in the Central and Eastern United States, AAPG Eastern Section Meeting, 2016,

٧٩٢ Wang, Z., Carpenter, N. S., Zhang, L., and Woolery, E. W.: Assessing Potential Ground-Motion Hazards
٧٩٣ from Induced Earthquakes, Natural Hazards Review, 18, 04017018, doi:10.1061/(ASCE)NH.1527-
٧٩٤ 6996.0000264, 2017.

٧٩٥ Yager, R. R.: On ordered weighted averaging aggregation operators in multi-criteria decision making, IEEE
٧٩٦ Transactions on Systems, Man and Cybernetics, B 18, 183-190, 1988.

٧٩٧ Zadeh, L. A.: Fuzzy sets, Information and control, 8, 338-353, 1965.

٧٩٨ Zadeh, L. A.: Fuzzy logic and approximate reasoning, Synthese, 30, 407-428, 1975.

٧٩٩ Zhu, X., and Dale, A. P.: JavaAHP: a Web-based decision analysis tool for natural resource and
٨٠٠ environmental management, Environmental Modelling and Software, 16, 251–262, 2001.

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٨١١ **Tables**

٨١٢ 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		

٨١٣
٨١٤
٨١٥ 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									

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

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a)

Predicted	Predominant Frequency (Measured)					
	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 %						

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b)

Predicted	Predominant Frequency (Measured)					
	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 %						

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854 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%

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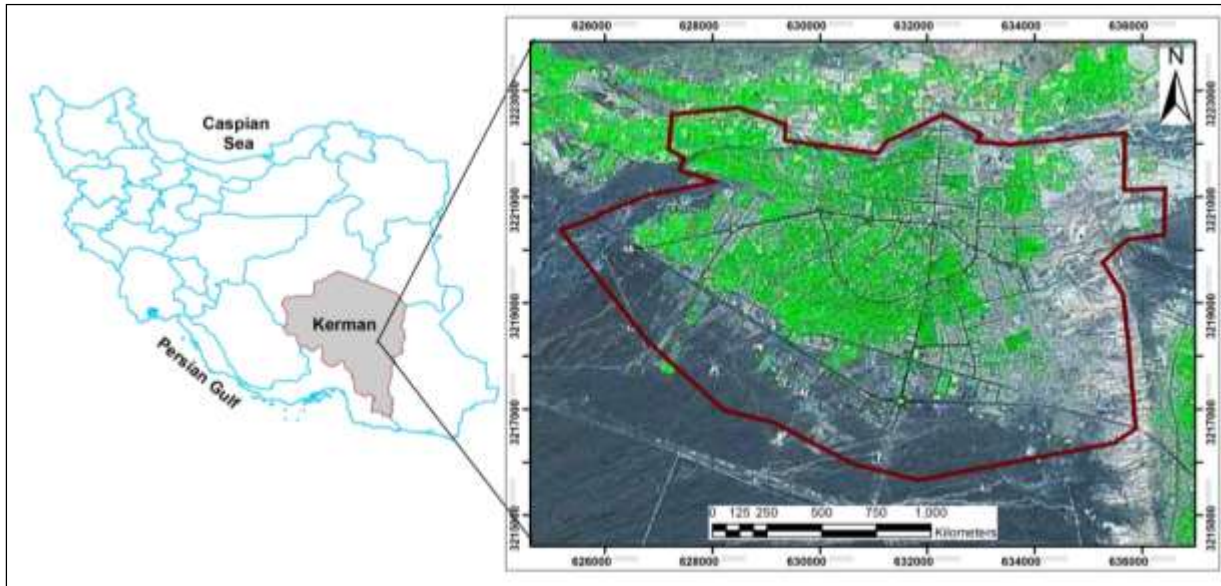
Figures
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Figure 1. The case study area of Bam City, Iran
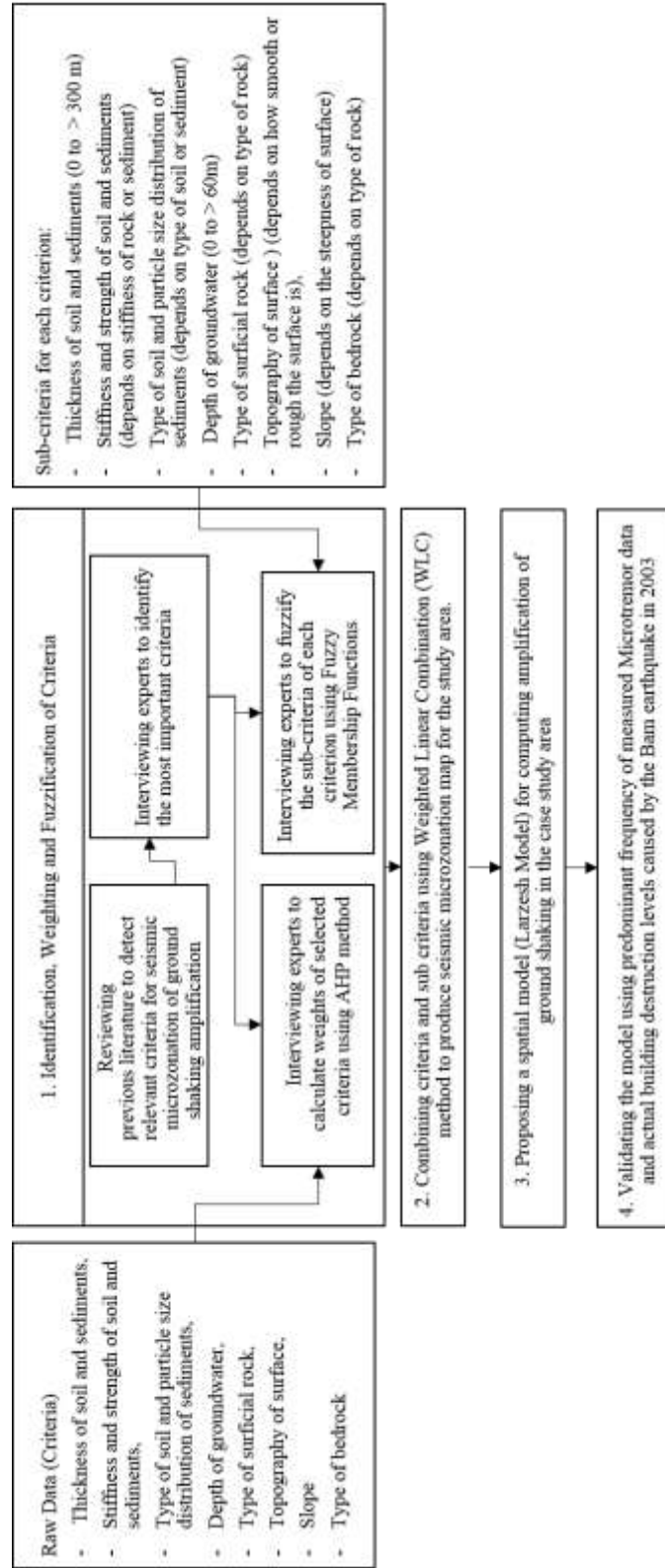
Figure 2. The methodological approach of the model

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

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

Figure 3.AHP matrix (A)
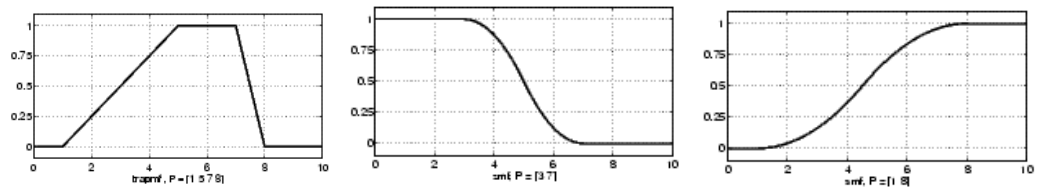
Figure 4. Fuzzy membership functions (After Mancini, 2012)
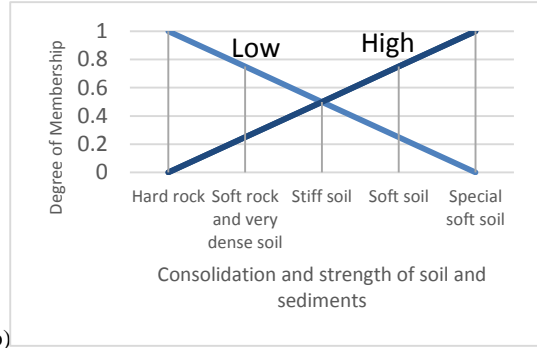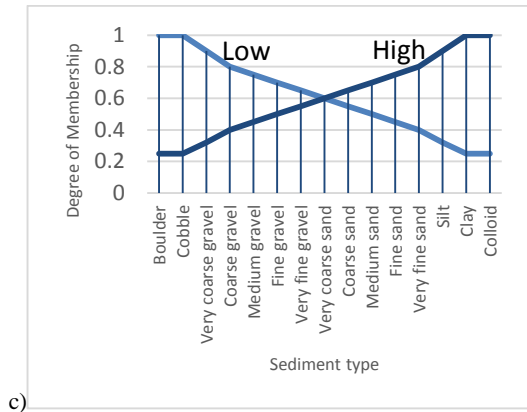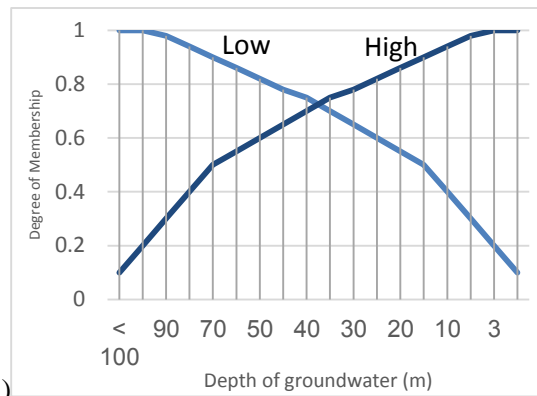
Figure 5. Membership functions (MFs) based on fuzzy logic system: Alluvial thickness

(a), Stiffness and strength of soil and sediments (b), Type of soil and particle size

distribution of sediments (c), Depth of groundwater (d).

a)

c)
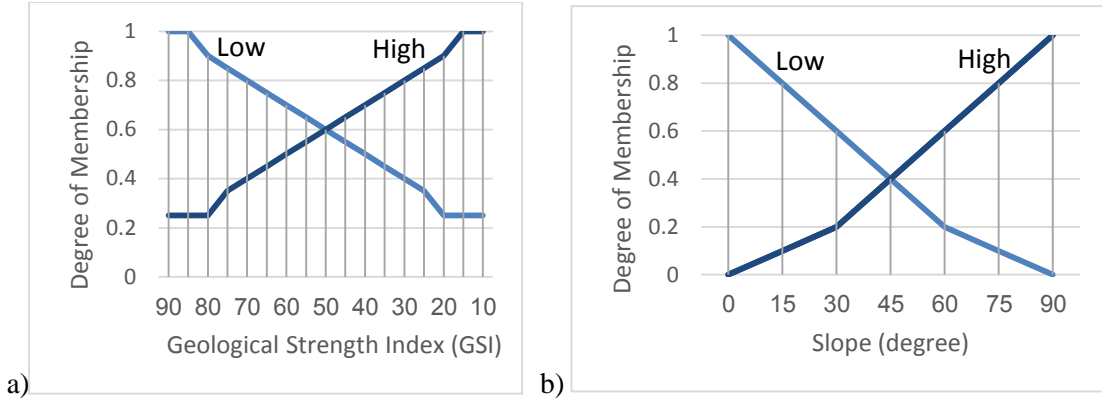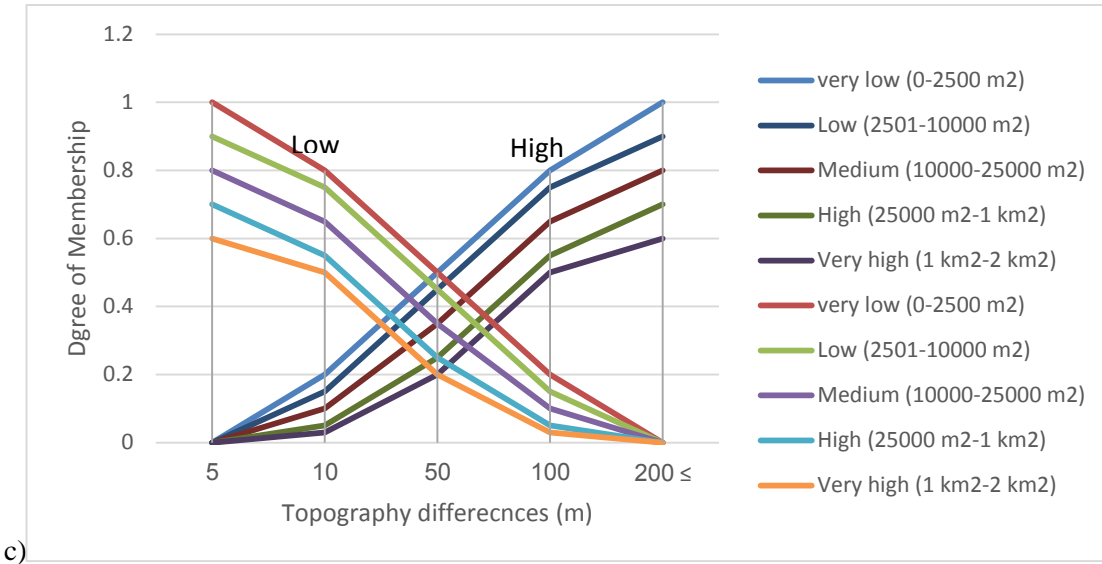
Figure 6. Membership functions (MFs) based on fuzzy logic system: Type of rock and

bedrock (a), Slope (degree) (b), Topographic irregularities (c).

٩٢٢   a)

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

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٩٢٧ a)

٩٢٨ b)

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

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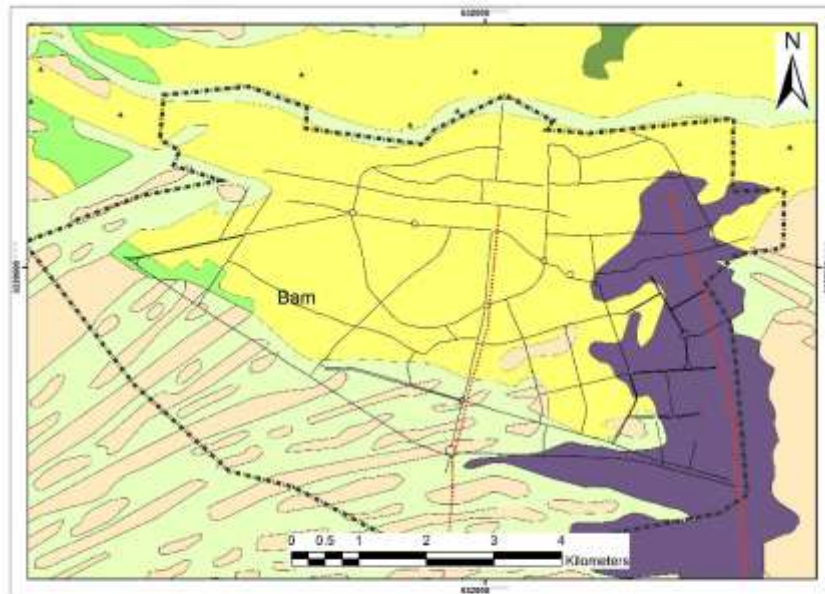
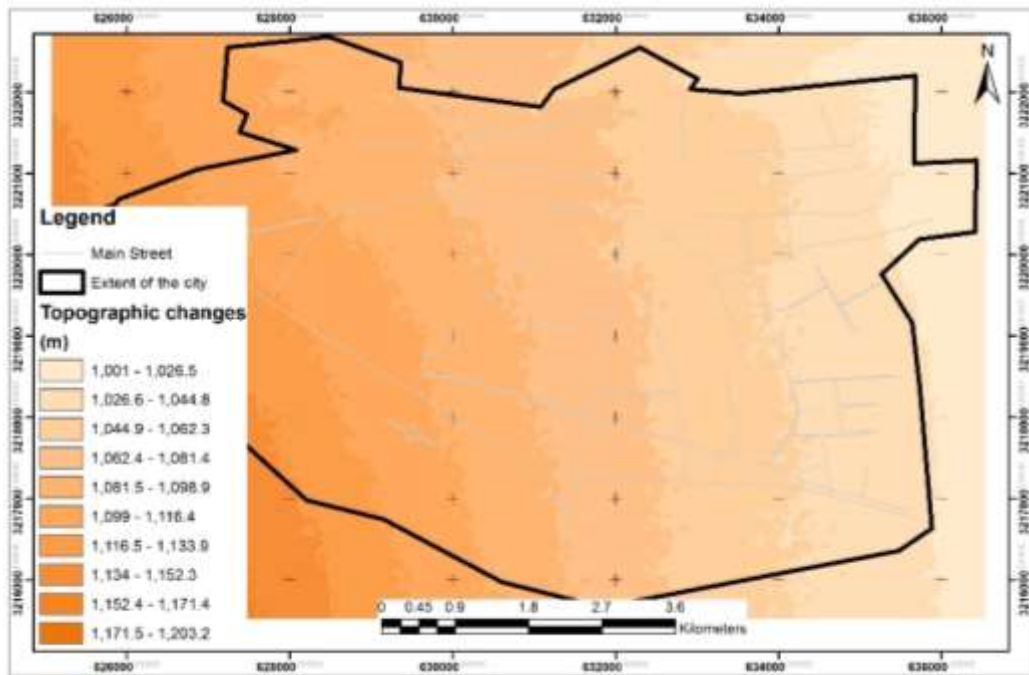
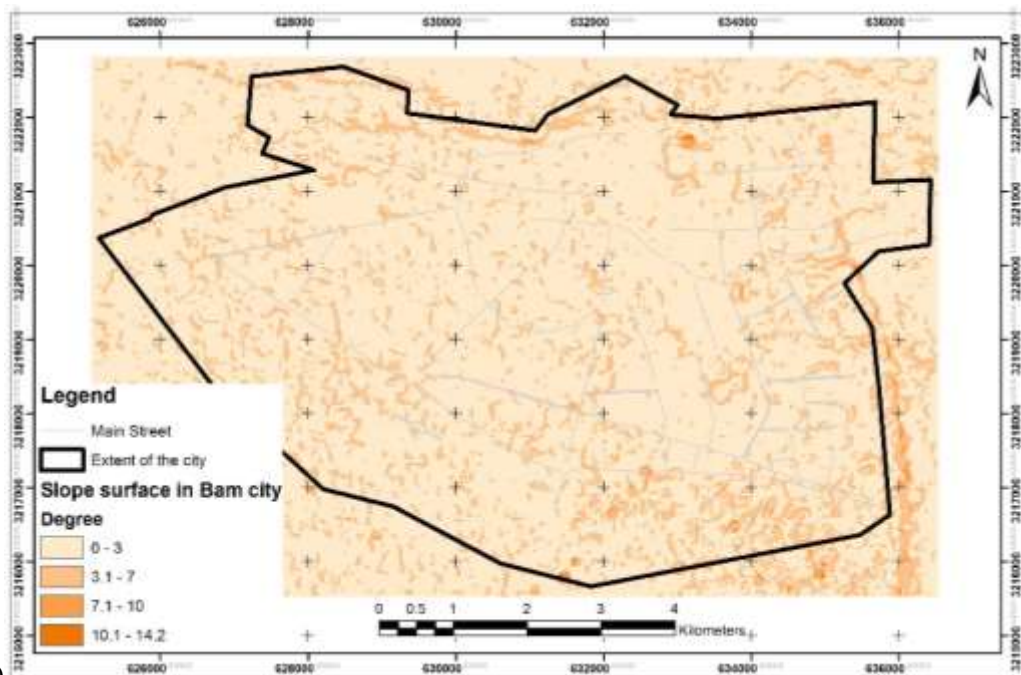
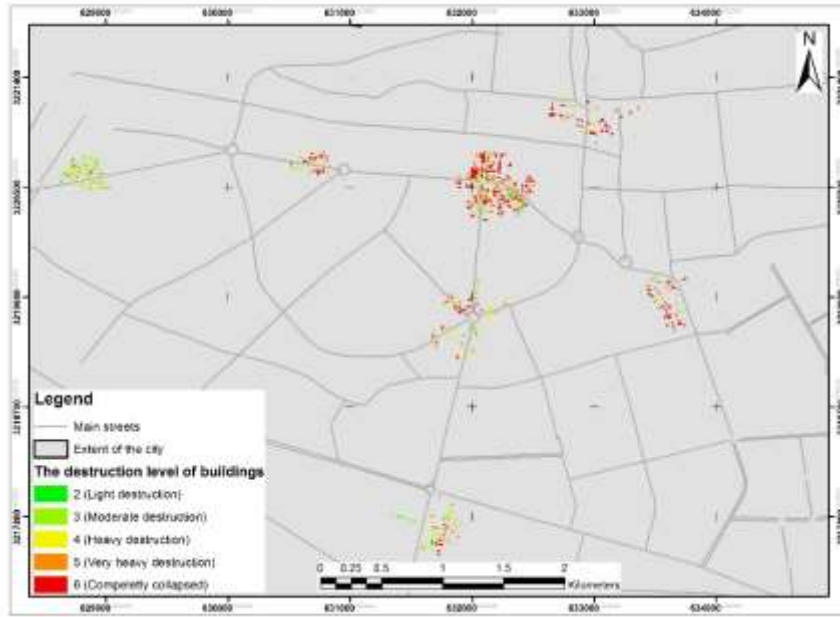
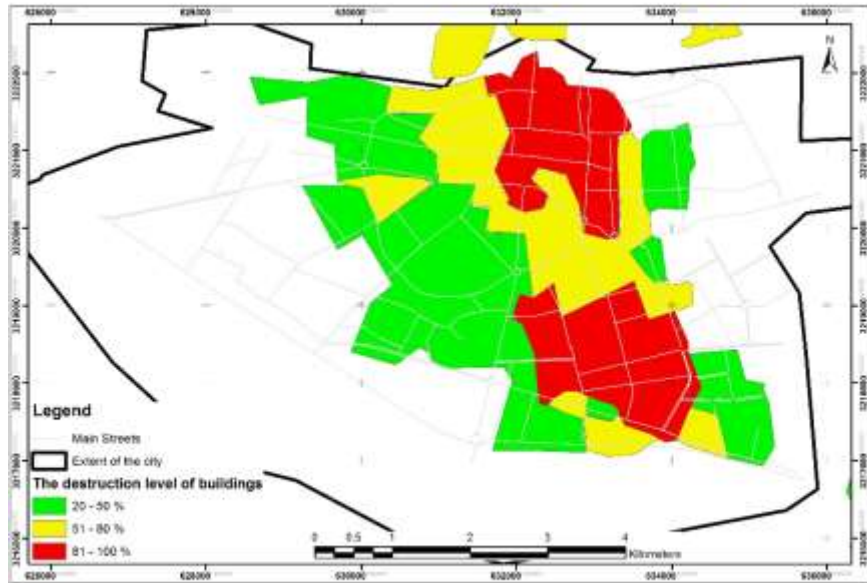
٩٣٢   a)

٩٣٣   b)

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

a)

b)

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

٩٤٢   a)

٩٤٣   b)

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

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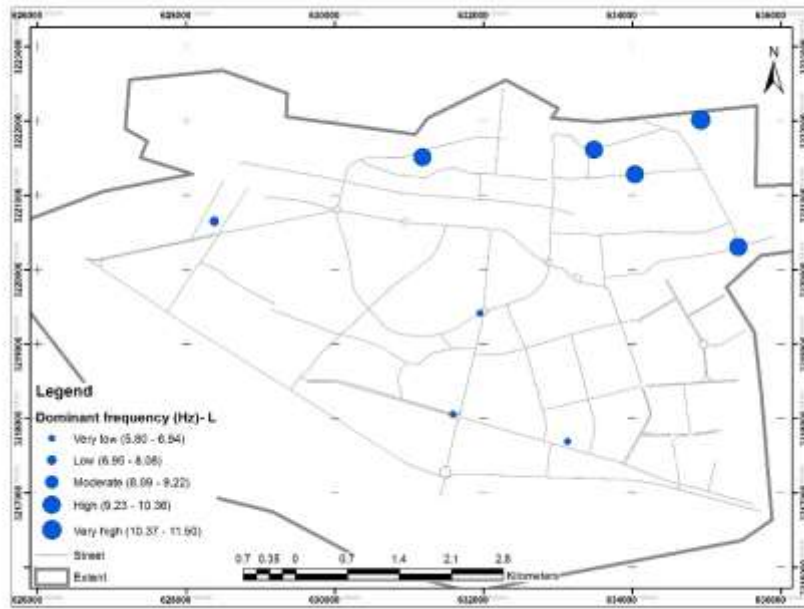
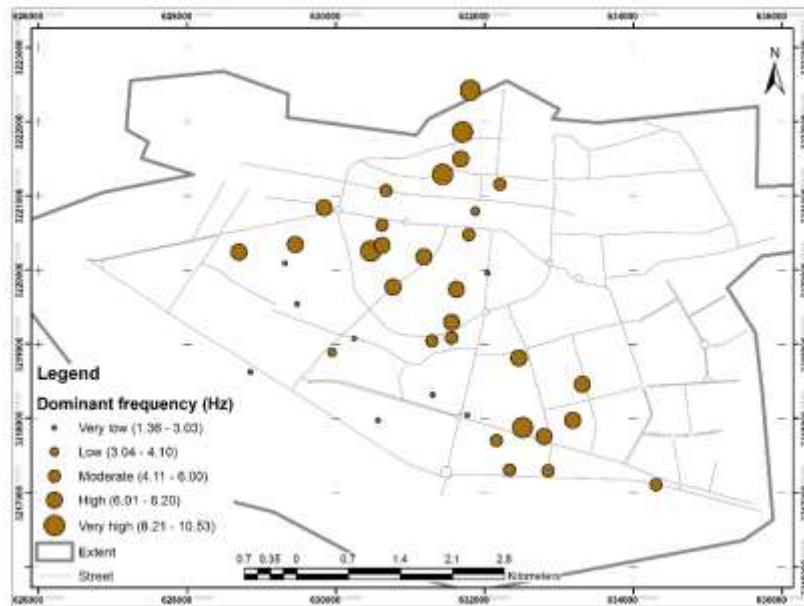
٩٤٩ a)

٩٥٠ b)
٩٥١ Figure 12. Control data: Dominant frequency by Lashkaripour (a) and by Motamed et al
٩٥٢ (Motamed et al., 2007) (b) using Microtremor field measurement.
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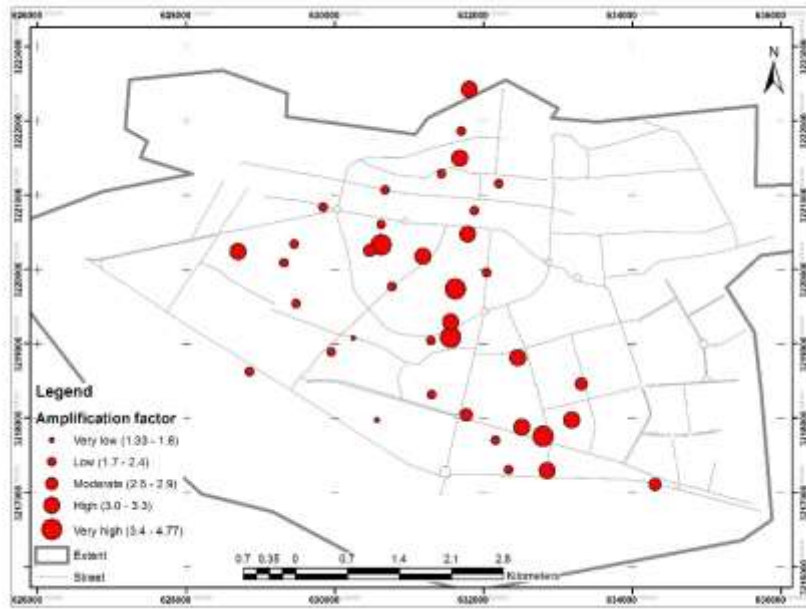
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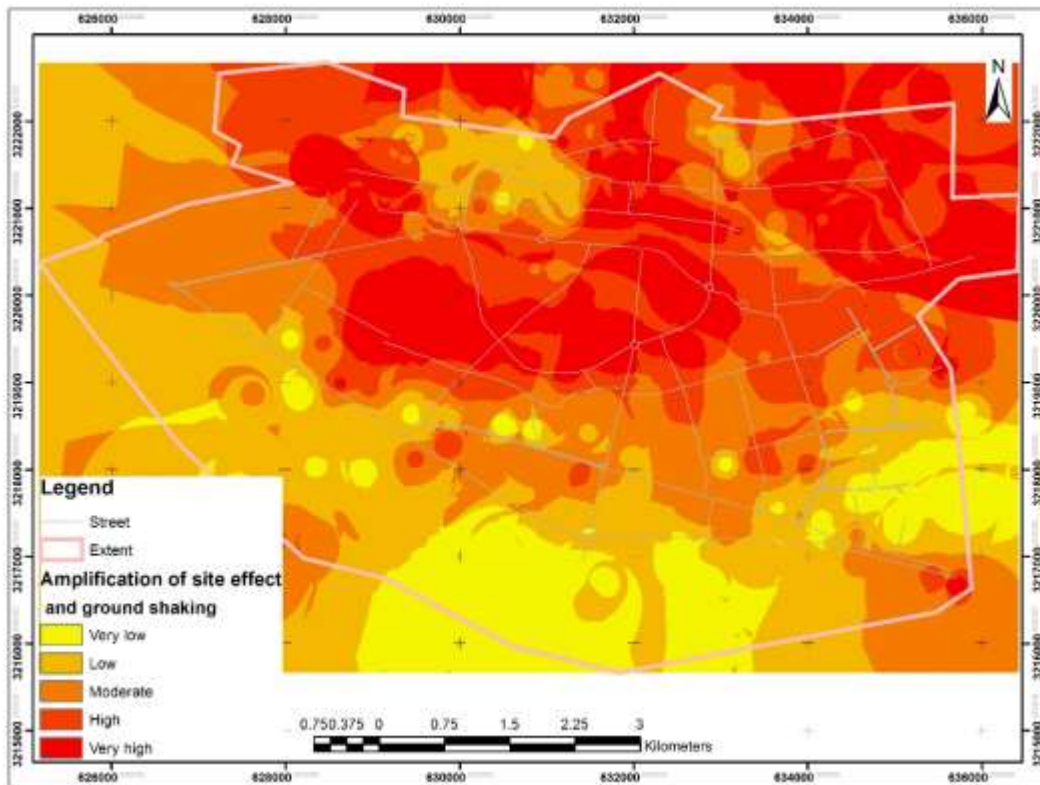
٩٥٥   e)
٩٥٦   Figure 13. Control data: Amplification factor by Motamed et al. (2007) using Microtremor field
٩٥٧   measurement.
٩٥٨

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