Fuzzy Inference System Approach in Deterministic Seismic Hazard, Case Study: Qom Area, Iran

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Abstract
Seismic hazard assessment like many other issues in seismology is a complicated problem, which is due to a variety of parameters affecting the occurrence of an earthquake. Uncertainty, which is a result of vagueness and incompleteness of the data, should be considered in a rational way. Using fuzzy method makes it possible to allow for uncertainties to be considered. Fuzzy inference system, is used since the study based on uncertainty estimation of seismic hazard for the region Qom, is done. First, the input parameters required for Seismic hazard assessment is fuzzified by fuzzification (in Matlab fuzzy tool-box) and the membership functions are used to set the degree of membership. The inference engine produces fuzzified sets using the output from the fuzzification stage and the rule base engine. The fuzzified sets are then defuzzified using the center of the area. Eventually, using a set of attained coordinates for the Holy Shrine (Masoumeh) a deterministic estimation of seismic hazard is made using both the usual deterministic approaches and the Mamdani fuzzy Inference System. Our results show a peak ground acceleration value of 0.43g using fuzzy inference system.

Keywords: Fuzzy Inference System, Seismic Hazard, Deterministic Approach, Peak Ground Acceleration

1. Introduction
The fuzzy set theory is one of the techniques that can be used to take into account the uncertainties existing in the phenomenon enter probabilistic or mathematical models. The fuzzy set theory was first introduced by L. A. Zadeh [1] who extended the classical concept of sets. Information is obtained from data, measurement or past knowledge, often be involved uncertainties. Fuzzy expert systems are modeled capable of solving problem as well as expert human.

Earthquake is one of the most destructive natural disasters that occur every several years and it causes vast human and financial losses. In such awfully status, it is necessary to investigate on different sight of an earthquake. Earthquake is a complicated problem, which is due to a variety of parameters affecting the occurrence of it, like seismic hazard assessment. Uncertainty, which is a result of vagueness and incompleteness of the data, should be considered in a rational way. Fuzzy logic can be modeled for two kinds of uncertainties (as low knowledge and human instrumentation
and as lack of perspicuity in complex phenomenon), whereas seismic hazard assessment (SHA) face with many uncertainties, using fuzzy logic system (FIS) can help us to take into account the uncertainty existed for solving problems.

The Iranian Plateau is one of the most seismically active areas of the world and frequently suffers destructive and catastrophic earthquakes that cause great loss of human life and widespread damage, it seems reasonable to pay attention to the seismic hazard in a seismogenic area of Iran. Seismic hazard may be analyzed using an empirical–statistical approach, or a probabilistic approach, or a deterministic approach, when a particular scenario is assumed, in which uncertainties in earthquake size, location, and distance of site to a source are explicitly considered. Because of the variety of parameters affecting the occurrence of earthquakes, seismic hazard assessment like many other matters in seismology is a complicated problem and subject to uncertainties. Uncertainty, which is a result of vagueness and incompleteness of the data, should be considered in a reasoning way. The fuzzy set theory is one of the techniques that can be used to take into account the uncertainties existed in the seismic hazard analysis.

In the present study, Fuzzy-logic system approach was applied for Deterministic Seismic Hazard (DSH) assessment of Qom region that it is the first time that fuzzy logic system is used in DSH assessment for Qom region.

The basis of DSH method is that the acceleration resulting from the earthquake created in each of the seismic sources in the site is determined and the largest one is presented as design acceleration. There are almost no probabilistic calculations in this method, so it’s been a popular way for both users and employers. The results of this research will be useful to the Qom Municipality Crisis Management Organization, Housing, and Development Research Center and determine of new building codes.

The fuzzy logic model in this study is established with inputs of maximum earthquake magnitude, shortest site-to-source distance and fault-type whereas the output is the horizontal component of Peak Ground Accelerations (PGA). In this study, we concentrate on the treatment of uncertainties related to the input and output parameters of DSH.

This paper is organized as follows: in Section 2, we review the application of fuzzy logic in seismic Hazard and another branch of science. We explain about methodology DSH and parameters in section 3.1. Then, in section 3.2 is elaborated FIS, all the variables in seismic hazard assessment are defined in terms of fuzzy sets. Then, with a knowledge base (database and rule base as the expert human) and inference engine are evaluated output parameter, and the output which is still fuzzy set will be defuzzified using the surface center method. The expected PGA value is calculated for a Qom region. In section 4, result and discussion are described and is compared the proposed model with other models. Finally, conclusions are done in Section 5.

2. Related Works

Today, fuzzy logic is used in various branches of science, such as Akhoondi and Hosseini [2] and Hoseini et al., [3] in medicine; Kalantari et al., [4] in computer science; Maghsoudi and Moshiri [5] in transportation and so on. Fuzzy set theory has been previously used in many issues about earthquake such as, quantify damage due to earthquake loads [6], fuzzy information on earthquake magnitude for determining earthquake recurrence relationships [7], quantify the uncertainties in structural models
and the subsequent response due to ground motions [8], risk assessment of urban natural hazards [9] and to earthquake response spectra models [10]. Recently it was used to develop to control seismic vibrations of small-scale buildings [11], to a classification of seismic damages in buildings [12], to seismic signal discrimination between earthquakes and quarry blasts [13].

Qom city signs to point of view holy shrine (Masumeh) and more passengers visit during the year. By the way, Qom has located adjacent the Tehran city (capital of Iran) which makes it capable of intensive earthquake damage in comparison with other regions. Several studies have been estimated the PGA for adjust area of Qom (Tehran), such as Zare [14], Ghodrati Amiri et al., [15] and Mirzaei [16]. They all have used the probabilistic methods for estimating PGA.

3. Methodology and Data

3.1 Deterministic Seismic Hazard (DSH) Analysis

Seismic hazard assessment (SHA) is a basic study for all other studies in various parts of geotechnics, structural, management and vast economical. The main goal of SHA is evaluating of ground motions parameters (peak ground acceleration, peak ground velocity and ...) in certain site [17].

In general, an SHA can be classified as either three methods to evaluate seismic hazard. Statistical-Empirical seismic hazard assessment or deterministic seismic hazard assessment and last method are probabilistic seismic hazard assessment. We used DSH method to evaluate seismic hazard in Qom area. The outline below are the steps involved in DSH analyses:

a. Identification of positional seismic source,
b. Determine the maximum magnitude earthquake($M_{\text{max}}$) and Shortest Distance (R) for each source,
c. Selection of attenuation relationship,
d. Computation of peak ground acceleration (PGA).

3.1.1 Identification of Potential Seismic Source

The description of a configuration of a potential seismic tectonic source (Rupturing the sources in the earth can cause an earthquake) requires much guidance such as tectonic geological, geophysical and earthquake data. A total of 232 potential seismic sources in Iran were delineated by Mirzaei et al., [18] and it improved up to 238 by Mousavi-Bafrouei et al., [19]. In this study, 23 of these area potential seismic sources located between 32.5°-37°N latitude and 48°-53.5°E longitude were used (Figure 1). Specifications of the seismic sources are taken in Table 1.
Figure 1. A potential seismic source in the study with maximum magnitude (M_{\text{max}}). The red circle represents the site of Holy Shrine.
Table 1: Number of Sources, Amounts of inputs and output parameters for each source.

<table>
<thead>
<tr>
<th>Source Number</th>
<th>Distance (Km)</th>
<th>M&lt;sub&gt;max&lt;/sub&gt;</th>
<th>Fault-type</th>
<th>PGA (g)</th>
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<tr>
<td>1</td>
<td>175.18</td>
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<td>0.27</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
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<td>6.0</td>
<td>0.062</td>
<td>0.19</td>
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<td>0.062</td>
<td>0.43</td>
</tr>
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</table>

b. Determine M<sub>max</sub> and Shortest Distance (R) for each source

In this step must evaluate of maximum magnitude, M<sub>max</sub> for each source that amount of M<sub>max</sub> determined as expert human. The shortest distance between each site-to-source was determined by coding in Matlab software. Holy shrine (Masumeh) was chosen as the site. M<sub>max</sub> and shortest distance for each source are taken in Table 1.
c. Selection of Attenuation Relationship

Determination of PGA needs to choose attenuation relationship which influences the result of SHA highly. An attenuation expression provides a functional relationship between earthquake properties and various parameters such as magnitude, site-to-source distance, and kind of fault, etc [17]. Attenuation relationship of Ambraseys et al., [20] is chosen by the expert human as follow:

$$\log Y = a_1 M + a_2 M_{\text{max}} + \left( a_3 + a_4 M_{\text{max}} \right) + \log R + a_5 S_s + a_6 S_a + a_7 F_N + a_8 F_T + a_9 F_O$$

Where $Y$ is peak horizontal ground acceleration in m/s$^2$, $S_s = 1$ for soft soil and 0 otherwise, $S_a = 1$ for stiff soil and 0 otherwise, $F_N = 1$ for normal faulting earthquakes and 0 otherwise, $F_T = 1$ for thrust faulting earthquakes and 0 otherwise, $F_O = 1$ for oblique faulting earthquakes and 0 otherwise, $a_1$-$a_{10}$ are constant coefficients that must be determined via regression analysis which is chosen as expert human that are as follow:

$$a_1 = 2.522, \quad a_2 = -0.142, \quad a_3 = -3.184, \quad a_4 = 0.314, \quad a_5 = 7.6, \quad a_6 = 0.137, \quad a_7 = 0.050, \quad a_8 = -0.084, \quad a_9 = 0.062, \quad a_{10} = -0.044$$

d. Computation PGA

The earthquake associated with the largest of site PGA is typically used to define the site design ground motion. The site design ground motion is determined by using the attenuation relationship to compute the PGAs corresponding to expected earthquakes with each source identified.

3.2 Fuzzy Logic System

Fuzzy logic is a complex mathematical method that allows solving difficult simulated problems with many input and output variables. Fuzzy logic allows for lower complexity by allowing the use of imperfect information in a sensible way. Fuzzy logic is an approach to computing based on degrees of truth rather the usual “true or false” Boolean logic on which the modern computer is based. When the linguistic variable is used, these degrees maybe managed by specific membership functions. A Fuzzy inference system is a system that uses fuzzy set theory to map inputs to outputs. There are two fuzzy inference systems, Mamdani and Sugeno. As regards, Mamdani’s fuzzy inference system is suitable for defined input by expert and it’s intuitive, we used Mamdani’s fuzzy inference system.

3.2.1 The Proposed Model

To compute the output of this method, one must go the following steps:

- Determining a set fuzzy rules by expert,
- Fuzzifying the inputs membership functions, (according to our data ranges for parameters and expert human idea, the bell membership function is considered),
- Aggregation of the rule outputs,
- Defuzzifying the output distribution (we used centroid defuzzification of area).

A schematic of fuzzy expert system components is shown as a flowchart in figure 2.
3.2.2 Linguistic Variables

In this study three of the input parameters including $M_{\text{max}}$, $R$ and $S$ (fault-type) are defined as fuzzy set by the discrete membership functions $\mu(M_{\text{max}})$, $\mu(R)$, $\mu(S)$, respectively. And PGA is output parameter for providing fuzzy inference engine is used. The values range of inputs and output parameters are defined base on knowledge of earthquake seismology and expert human.

a) Input parameters

We choose the amount of distance site-to-source between Zero to 250km. We used four bell membership functions with a range of, near, medium, far and very far as figure 3.

Figure 2. A schematic of fuzzy expert system components

Figure 3. Membership functions for R (distance site-to-source).
Amount of maximum magnitude between 4.5 to 8.5 is chosen. So, five bell membership functions with ranges of short, medium, large, very large and very very large are used within the show in figure 4.

![Figure 4. Membership functions for $M_{\text{max}}$.](image)

Three main fault-type exist (Normal, Reverse, Oblique), so three bell membership functions considered with ranges of Normal, Reverse and Oblique (Figure 5).

![Figure 5. Membership functions for $S$ (fault-type).](image)

**b) Output parameter**

Amount of output parameter, PGA is considered between zero to 0.9g (g is ground acceleration, $\sim$9.8 m/s²). Six bell membership functions with ranges of very low, low and medium, much, very much and very very much are used (Figure 6).
3.2.3 Design of Set Fuzzy Rules

According to our data set, 60 set fuzzy rules are defined by the expert human. The inference rules in the fuzzy logic system are defined through “If-Then” clause. Some fuzzy rules which are used for fuzzy inference engine are defined as follows:

- If (distance is near) and (M\textsubscript{max} is short) and (fault-type is thrust) then (PGA is low),
- If (distance is near) and (M\textsubscript{max} is medium) and (fault-type is thrust) then (PGA is medium),
- If (distance is near) and (M\textsubscript{max} is large) and (fault-type is thrust) then (PGA is much),
- If (distance is near) and (M\textsubscript{max} is very_large) and (fault-type is thrust) then (PGA is very_very_much),
- If (distance is near) and (M\textsubscript{max} is very_very_large) and (fault-type is thrust) then (PGA is very_very_much),
- If (distance is near) and (M\textsubscript{max} is short) and (fault-type is normal) then (PGA is very_low),
- If (distance is near) and (M\textsubscript{max} is medium) and (fault-type is normal) then (PGA is very_low),
- If (distance is near) and (M\textsubscript{max} is large) and (fault-type is normal) then (PGA is low),
- If (distance is near) and (M\textsubscript{max} is very_large) and (fault-type is normal) then (PGA is much),
- If (distance is near) and (M\textsubscript{max} is very_very_large) and (fault-type is normal) then (PGA is much)
4. Experimental Results

4.1 Results

Given the above problem, namely, calculating PGA for Qom city and in particular the holy shrine area and given the uncertainty of the data sets and other circumstances it was therefore decided to use Mamdani fuzzy inference system and this was implement in Matlab tool-box. Figure 7, is an example of the various stages of the output obtained for source 6 (Figure 1), using distance, $M_{\text{max}}$ and the fault type with values of 40.07 km and 6.5 and 0.062 (thrust) respectively.

Using the above process, the PGA was calculating for all 23 sources and is shown in Table 1.

Figure 8, shows a 2D view of relationship PGA has with input parameters (a) distance, (b) $M_{\text{max}}$ and (c) fault-type. In part 8-a, the graph is descending that is shown acceleration decreasing with distance from the source which is good agreement with attenuation relationship. While in 8-b, the graph is ascending that is shown acceleration increasing with $M_{\text{max}}$. In the last part of figure 8-c, is shown that reverse fault made more acceleration rather than other fault-type and good agreement with seismological evidence.
Figure 8. 2D graphs of the fuzzy logic systems input-output system. a) The horizontal axis is shown site-to-source distance. b) The horizontal axis is shown $M_{\text{max}}$. c) The horizontal axis is shown fault-type. A vertical axis is PGA in all parts.

Figure 9 shows a 3D view of the relationship PGA has with (a) $M_{\text{max}}$ and distance, (b) fault type and (c) $M_{\text{max}}$, fault-type and distance. Figure 9 also shows that when $M_{\text{max}}$ is increased and fault type is thrust, the PGA value is increased.
According to the results of a deterministic seismic hazard estimation using fuzzy logic, we plotted contour map of PGA based on values of PGA for each source in Qom region (Figure 10). Figure 10 indicates that the maximum horizontal acceleration of Qom province varies between 0.16g to 0.43g for Holy Shrine site. The largest value of PGA is the 0.43g belongs to source 6 with the $M_{\text{max}}$ value of 6.5 and the distance of 40.07 km.
4.2 Discussion of the Results

Since the seismic hazard assessment in Qom area has not been evaluated, we will not have the chance to compare our results with previous studies in Qom area, but comparisons can be made with studies in adjacent areas that include the Qom area.

In the global seismic hazard map (1992), Qom is situated in the region with a high seismic hazard which adjusted our result. According to PGA zonation map of Iran [21], Qom is located in the area with high relative risk. It also works mentioning that the overall value obtained for Qom city using the usual deterministic approaches was 0.43g. Some seismic hazard studies have been done for Iran that is considered our study area, yielding to different results based on data set and method, like [19], [22], [25]. All of those studies have well correlated with our study. Boostan et al., [26], [27] studied Fuzzy-probabilistic seismic hazard assessment for Tehran region and suggested PGA adjacent the Qom area is equal to 0.45-0.50g. Recently, Mousavi-Bafrouei et al., [19] studied on seismic hazard zoning in Iran and estimating PGA in provincial capitals, so evaluated PGA=0.4-0.6g in our study area. Our result is in close relation with overall values obtained from Qom city.

Figure 10. The contour map of PGA as fuzzy logic.
In addition, the fuzzy system is flexibility based on expert knowledge to solve problems, simplifies the process of deterministic seismic hazard and considering the uncertainties, it improved the accuracy and was a big help to the seismologist.

5. Conclusion

Seismic hazard assessment like many other issues in seismology is a complicated problem due to a variety of parameters affecting the occurrence of an earthquake. Uncertainty, which is a result of vagueness and incompleteness of the data, should be considered in a rational way. Herein, the fuzzy set theory was used to take into account the uncertainty existed in the seismic hazard analysis of Qom region. It should be emphasized that the FIS approach in DSH revealed the ability of the FIS to consider the uncertainties in the input and output parameters. This method showed that maximum value of PGA is the 0.43g belongs to the source with a $M_{\text{max}}$ value of 6.5 and the distance of 40.07 km relative to Holy Shrine.

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References


