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SEISMIC HAZARD ANALYSIS BASED ON FUZZY-PROBABILISTIC APPROACH

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Abstract. *China is a country prone to frequent earthquakes due to geography and climate complexity. The task of seismic hazard analysis is to estimate the potential level of ground motion parameters that would be produced by future earthquakes. In this paper, a novel method for seismic hazard analysis is proposed based on the fuzzy probabilistic approach. The earthquake magnitude and source-to-site distance are defined as fuzzy-random variables. Further, Cornell model is applied to evaluate the ground motion and the fuzzy-probability of exceedance of the peak ground acceleration level. The advantage of the fuzzy probabilistic seismic hazard analysis model over the traditional deterministic and probabilistic seismic hazard models is that it considers two types of uncertainties, aleatory and epistemic. The proposed model investigates the seismic hazard of Kunming, the capital of Yunnan province in China.*

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1 INTRODUCTION

Earthquakes are one of the most frequent natural disasters. Seismic hazard analysis estimates the level of ground-motion intensity parameters such as peak ground acceleration PGA, peak ground velocity PGV that would be produced by future earthquakes[1]. The purpose of seismic hazard analysis is to ensure that the civil structures and infrastructure systems withstand an earthquake of the specific return period, perform a desired level of functionality and enable fast recovery to full capacity.

In the current literature, two approaches have been used for evaluating seismic hazard. The Deterministic Seismic Hazard Analysis (DSHA) is applied in the case when the single earthquake scenario for the particular site is considered. This method assumes deterministic information about the earthquake size and source-to-site distance [2]. Also, the single earthquake scenario which is chosen for analyzing represents the “worst-case” scenario. However, the disadvantage of this method is the lack of information about the likelihood of the occurrence of controlling earthquake and the effects of uncertainties involved such as uncertainties in the earthquake size, source location, source-to-site distances and resulting shaking caused by earthquakes [3]. Furthermore, the “worse-case” scenario is not enough for its use of the mean motion when field evidence has pointed out the observed motion exceeding two standard deviations above the mean [4]. The socio-economic impacts of earthquakes for relatively small regions which are bordering specific seismic sources could be estimated by DSHA since this method is useful for the particular case. However, it is impossible to predict the exact future earthquakes and earthquake randomness is of high aleatory uncertainties [5]. In order to account these uncertainties, the Probabilistic Seismic Hazard Analysis (PSHA) is used. It analyzes different earthquake scenarios which vary in the earthquake size, source-to-site distance, and ground motion models in order to predict the most probable value of future ground shaking. The aleatory uncertainties of the earthquake magnitude, the source-to-site distance and wave attenuation have been taken into account by this method [6]. Further, this method has been prescribed as part of site-specific earthquake resistant design [7]. On the other hand, the PSHA is potentially critical when it comes to the epistemic uncertainty [8]. Besides aleatory uncertainty, the epistemic uncertainty arises due to the lack of information about the earthquake size and location. The characteristic of epistemic uncertainty is fuzziness [9].

The aim of this paper is to bridge the gap in the existing analysis methods and to propose the fuzzy probabilistic seismic hazard analysis (FPSHA) approach. A novel seismic hazard analysis method is based on the fuzzy-probabilistic approach. The proposed method represents the upgrade of the existing methods, in which the concepts from the fuzzy sets and probabilistic theory have been applied to estimate the potential seismic hazard. The aim of the fuzzy set theory is to solve high uncertainty problems, represent vague, ambiguous, conflicting and chaotic information, handle imprecise data and information possessing non-statistical uncertainties[10-12]. The motivation to apply fuzzy set theory has its origin in its effectiveness and reliability. Fuzzy-probability approach has verified as the efficient tool in risk assessment in construction industry [13], seismic resilience assessment [14, 15], safety assessment of structures [16], flood risk assessment [17], risk assessment for oil and gas [18], design of water distribution network [19], human health risk assessment [20] and others.

The paper is organized as follows: Chapter 2 reviews the existing methods for the seismic hazard analysis, the deterministic and the probabilistic seismic hazard analysis. Further, Chapter 3 introduces the proposed method for fuzzy-probabilistic seismic hazard analysis. The case study about the seismic hazard in Yunnan Province in China is investigated in Chapter 4. The Chapter 5 provides the conclusions and further research.

2 LITERATURE REVIEW

The DSHA investigates one or more critical earthquake scenarios for which a ground motion hazard evaluation is based. The earthquake scenario is determined by the occurrence of an earthquake of a specified size at a specified location. To estimate the site ground motions, the magnitude, the source-to-site distance and site characteristics are included [21]. The DSHA is a simple straight-forward procedure which is usually used for evaluation of worst-case scenario of ground motions.

The DSHA is a four-step process:

- Identification and characterization of seismic sources which produce significant ground motion on the site;
- Source-to-site distance for each source zone which can be distance from hypocenter-to-site or distance from epicenter-to-site;
- Levels of shaking produced by earthquakes;
- Definition of hazard in terms of the ground motion parameters (PGA, PGV and response spectrum) obtained from attenuation relationships.

The PSHA approach estimates the annual frequency of exceedance as a function of a ground measures, such as spectral acceleration or peak ground acceleration based on seismological and geological data [22]. The uncertainties about the size of earthquakes, location and recurrence rate of earthquakes are identified, quantified and combined in the procedure of the PSHA. The PSHA is similar to DSHA since it consists of four steps which are similar. Compared to DSHA, all possible earthquakes scenarios of each source are characterized and described by probability distribution.

The PSHA procedure includes steps as follows [23]:

- All earthquake sources are identified and the probability distributions of potential rupture locations are characterized. Earthquakes are equally likely to occur at any point within the source zone, so uniform probability distribution is assigned to each zone. Further, the probability distribution of source-to-site distance is determined.
- Seismicity of the source zones are characterized by recurrence relationship which provide the average rate of earthquake of a particular magnitude will be exceeded.
- Attenuation relationships are used to determine the ground motion produced at the site of interest considering earthquakes of any possible magnitudes in any possible point of the source zone.
- The uncertainties about the earthquake size, location and ground motion parameters are combined to obtain the total probability or exceedance rate of the ground motion parameter.

3 FUZZY-PROBABILISTIC SEISMIC HAZARD ANALYSIS (FPSHA)

Generally, the proposed procedure for FPSHA is the extension of the PSHA method, in which the concepts from the fuzzy sets theory are applied to treat the epistemic uncertainty. Fuzzy set theory is introduced by Zadeh [24]. According to him, fuzzy set theory is "***a theory in which everything is matter of degree or everything has elasticity***"[25]. Fuzzy sets is defined as the class with a continuum of membership grades [26]. Membership function is defined as the function which ties a number to each element of the universe. This number indicates the degree of the element belonging to a fuzzy set.

The magnitudes of earthquakes that have been occurred at the fault can be extracted from historical geological data or measured by instruments. This information is used for predicting the size of future earthquakes. Since there is a variety of data about the earthquakes which already occurred, the dominant uncertainty for predicting earthquake magnitudes is randomness.

In the following model, randomness is extracted from the previous earthquake occurrence which delivers an estimated probability *M*. Additionally, the estimated probability could be accompanied by some measures of uncertainty such as imprecise probabilities in the form of interval [3]. Beside randomness, also fuzziness is included in the model for predicting earthquake magnitude. To include fuzziness of magnitudes, the point probability of magnitude is modeled in form of fuzzy number. Further, the epistemic uncertainty rises due to the lack-of-knowledge of the seismic source location. The lack-of-knowledge of the source-to-site distance is modeled in terms of fuzzy sets and for each fuzzy set, corresponding probability is attributed. In conclusion, the fuzzy-randomness in the process of seismic hazard analysis is handled by ascribing fuzzy probability density functions to earthquake magnitudes and source-to-site distances.

The fuzzy probabilistic seismic hazard analysis (FPSHA) is established and the flowchart is depicted in Figure 1. In the given flowchart, the first step is to identify all possible locations of the sources on the fault which are capable producing earthquakes to the site of interest. Once when the earthquake sources are recognized, the seismic occurrence probability is estimated using the historical seismicity data.

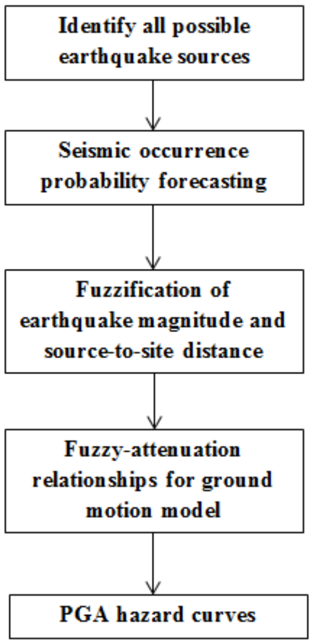

Figure 1 Flowchart of fuzzy-probabilistic seismic hazard analysis

Further, fuzzification the probability distribution of the earthquake magnitudes that are estimated by observed data for the particular site or using fuzzify G-R recurrence law for predicting the fuzzy probability of exceedance:

- fuzzify the probability distribution of the source-to-site distance;
- predict the resulting fuzzy distribution of ground motion intensity as a function of earthquake magnitude and location distance;
- combine all uncertainties including fuzziness in earthquake size, location and ground motion using a theorem known as total fuzzy probability theorem in order to estimate fuzzy hazard curves;
- estimate the fuzzy probability of exceeding certain levels of PGA.

3.1 Earthquake sources and seismic occurrence probability forecasting

This step is similar to the first step in the PSHA which task is to identify all possible sources that contribute to producing ground motions at the particular site. These sources are faults which can be determined from the past earthquake locations and geology data. If the faults could not be identified than the earthquake sources are described by areal regions. The earthquake sources are described as point sources which distance from the site could be model as fuzzy distance. The fuzzy-distance takes the range of values since earthquakes are equally likely to occur at any point within the source zone.

After the earthquake sources are determined, the next step in flowchart is to evaluate the probability of earthquake occurrence. The probability of occurrence of earthquakes with specific magnitude is based on the analysis of historical seismicity records. The future time series will have the similar distribution to the observed one if it is assumed that the past and future data sets are stationary.

The seismic occurrence probability forecasting model is estimated based on the historical earthquakes data. The historical earthquakes data can be found in different earthquakes catalogs. The catalog of seismic events is required in order to calculate the seismicity parameters for region of interest. In earthquake catalog, the historical data of seismicity, global and local earthquake records are collected and stored. Earthquake catalog is a list that provides the information of recorded earthquakes: time of occurrence (year, day, time), longitude and latitude of location, focal depth, earthquake size – magnitudes [27]. From the catalog, it could be derived recurrence relations for predicting annual rate of earthquakes of different magnitudes within a source zone. Further, the obtained information is used in the procedure of FPSHA. The data for the earthquake catalogs could be obtained from the US Geological Survey (USGS) [28], National Centers for Environmental Information - National Oceanic and Atmospheric Administration (NOAA)[29] and etc.

3.2 Fuzzification of Magnitude and Source-to-site Distance

Fuzzification is the process of converting crisp magnitude values from into the fuzzy triangular numbers. The pointed value of the magnitude is extended to the range of value so the confidence interval is obtained for any level. For a given point value of magnitude, the fuzzy value is modeled in form of a symmetric triangular fuzzy number, in which the center is the point value of magnitude $\overline{M}$ and left and right bound of supports are given in the form [$\overline{M}$ - s, $\overline{M}$ + s], where s is the uncertainty factor. The uncertainty factor s is constant estimated by the experts' opinion which takes value between 0 and 1, and usually equal to 0.5.

Earthquake magnitudes are defined as fuzzy triangular numbers which are expressed by the following formula:

$$\tilde{M} = (M - 0.5, M, M + 0.5) \quad (1)$$

The membership function for the fuzzy triangular magnitude is given as:

$$\tilde{M} = \begin{cases} 0, \quad m < M - 0.5 \\ \dfrac{m - (M - 0.5)}{(M + 0.5) - (M - 0.5)} = \dfrac{m + 0.5 - M}{1} = m + 0.5 - M, \quad M - 0.5 < m < M \\ 1, \quad m = M \\ \dfrac{(M + 0.5) - m}{(M + 0.5) - (M - 0.5)} = M + 0.5 - m, \quad M < m < M + 0.5 \\ 0, \quad m = M + 0.5 \end{cases} \quad (2)$$

To estimate ground shaking at a particular site, it is necessary to model the distribution of distances from earthquake fault to the site of interest. When it comes to modeling source-to-site distance, it is assumed that earthquakes occur with the same probability at any location on the fault [23]. This assumption is taken from the PSHA. Furthermore, Satriano, et al. [30] have showed that uncertainties associated with the source-to-site distance can be negligible compared to those associated to magnitude.

In the FPSHA method, the source-to-site distances are fuzzified and modeled as fuzzy sets with a triangular shape of membership function. Further, a probability to each fuzzy set has been prescribed based on studies of seismic zones in the area. According to the engineering judgment, it is customarily used the source-to-site distance threshold of 200 km [31]. All seismic zones with 200 km range have been considered in the source model. Further, the linguistic scale for distances classification is developed as highlighted in Figure 2. In this paper, we propose 11 different fuzzy sets to describe the distance between the potential source and site. For each fuzzy set, the membership function is prescribed as follows:

$$\tilde{R} = \begin{cases} 0, & r < R_1 \\ \dfrac{r - R_1}{R_2 - R_1}, & R_1 < r < R_2 \\ 1, & r = R_2 \\ \dfrac{R_3 - r}{R_3 - R_2}, & R_2 < r < R_3 \\ 0, & r > R_3 \end{cases} \tag{3}$$

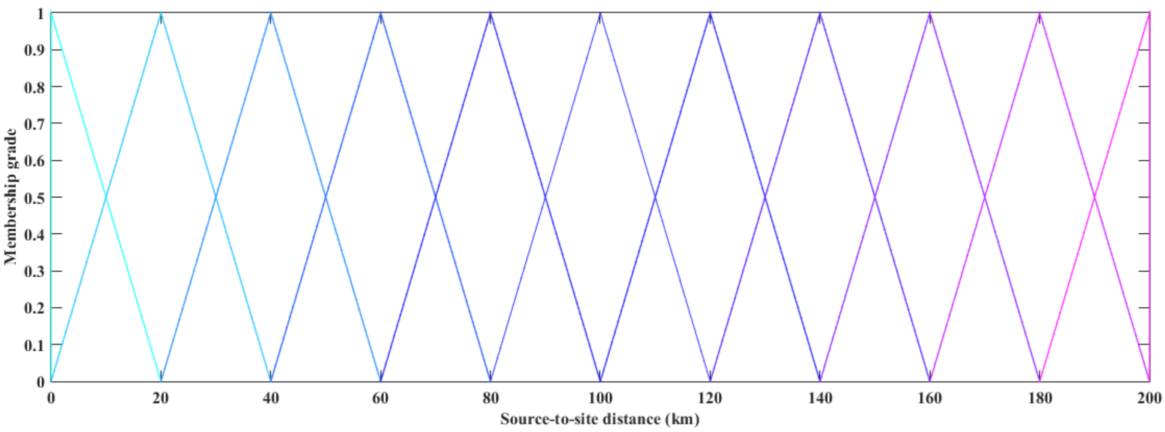

Figure 2 Fuzzification of the source-to-site distances

3.3 Fuzzy Recurrence law

The likelihood of the magnitudes that could occur at the particular site is determined by the Gutenberg-Richter (G-R) recurrence law. Since the magnitudes are given as fuzzy sets, the G-R recurrence law should be extended in order to operate with fuzzy numbers. The extension of the recurrence law for fuzzy magnitudes gives fuzzy recurrence law:

$$\log \tilde{\lambda}_m = \tilde{a} - b\tilde{m} \tag{4}$$

where, $\tilde{m}$- fuzzy magnitudes; $\tilde{\lambda}_m$ -the fuzzy rate of earthquake occurrence with magnitudes greater than *m*, constant *'$\tilde{a}$'* – the fuzzy rate of earthquakes in region; and constant *'b'* - the relative ratio of small and large magnitudes. The '$\tilde{a}$' and '*b*' constants are estimated using statistical analysis of historical observations. The value of '*b*' depends on the continent plate.

The proposed equation is used to estimate the fuzzy probability ratio of the earthquake occurrence. Further, fuzzy probability distribution function is derived from the fuzzy recurrence law in order to describe the membership degree of earthquake magnitude (the value of belonging the of earthquake magnitude to the fuzzy set) to certain level of probability of exceedance for that magnitude value.

Recalling the fuzzy probability theory, the fuzzy probability cumulative distribution function of magnitudes can be calculated by following equation:

$$\tilde{F}_M(\tilde{m}) = \frac{1-10^{-b(\tilde{m}-\tilde{m}_{min})}}{1-10^{-b(\tilde{m}_{max}-\tilde{m}_{min})}} \quad (5)$$

where, $\tilde{m}_{min}$ - minimum fuzzy magnitude value; $\tilde{m}_{max}$ - maximum fuzzy magnitude value; $\tilde{F}_M(\tilde{m})$ - fuzzy probability cumulative distribution function.

Further, the continuous distribution of magnitudes is transformed to a discrete fuzzy set of magnitudes. The first step in order to estimate the fuzzy probabilities of the exceedance is to fuzzify earthquake magnitudes. The earthquake magnitudes are converted into fuzzy values according to the formula (1). After fuzzification, the earthquake magnitudes are given in Figure 3.

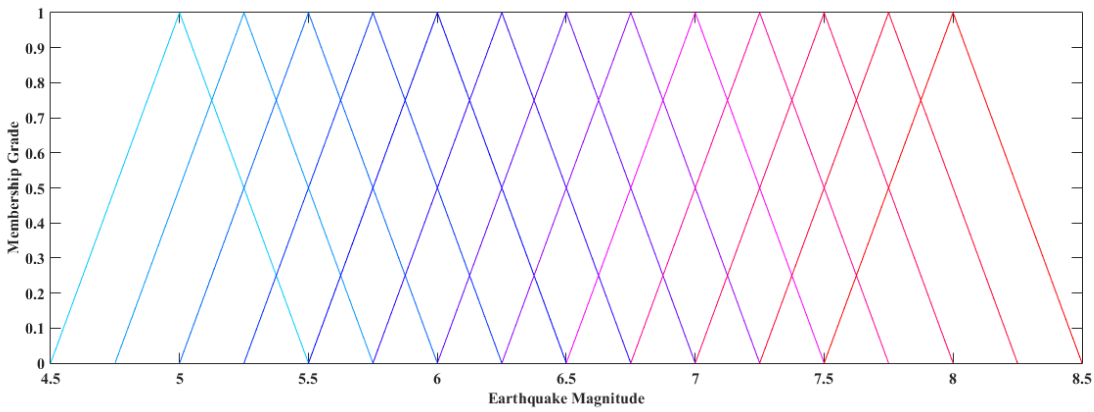

Figure 3 Linguistic scale of earthquake magnitudes

The magnitude threshold of $5.0M_w$ is adopted due to the fact that earthquakes with magnitude smaller than 5.0 could cause small damages to structures [6]. Applying the formula (1), the threshold for fuzzy magnitude is equal to (4.5, 5.0, 5.5). Further, for the magnitude increment, ten bins is used as in a benchmark PSHA example [2]. The magnitude increment is estimated by expression:

$$m_{inc} = \frac{m_{max}-m_0}{10} \quad (6)$$

The maximum magnitude is selected from the earthquake catalog. The probabilities of occurrence of fuzzy sets of magnitudes are computed by the following equation:

$$\tilde{P}(\tilde{M} = \tilde{m}) = \tilde{F}_M(\tilde{m}_{j+1}) - \tilde{F}_M(\tilde{m}_j) \quad (7)$$

3.4 Ground motion models

Ground motion prediction models have been used to estimate ground motion intensity and to develop PGA hazard curves. A total three attenuation relationships models have been considered and used to develop the PGA hazard curves. These models have been adopted to predict a fuzzy probability distribution of the ground motion intensity as a function of variables such as magnitudes, the source-to-site distances and fault mechanisms. In the models, magnitudes and source-to-site distances are calculated through fuzzy probability distribution and given by fuzzy triangular numbers.

The predictive model for the mean of log peak ground acceleration proposed by Cornell, et al. [32] is adopted for the case of fuzzy triangular values of magnitudes and source-to-site distances. The model is extended in order to predict the fuzzy probabilities of the peak ground motions. The proposed fuzzy probabilistic predictive model of log peak ground acceleration is:

$$\widetilde{lnPGA} = -0.152 + 0.859\tilde{M} - 1.803\ \ln(\tilde{R} + 25) \tag{8}$$

where, $\tilde{M}$ and $\tilde{R}$ - fuzzy random variable presenting the earthquake magnitude and distance from earthquake fault, $\widetilde{PGA}$ – fuzzy random peak ground acceleration.

The standard deviation of *lnPGA* was 0.57 in the Cornell, et al. [32] model and it was constant for all magnitudes and distances. Also, the standard deviation of ln$\widetilde{PGA}$ for every membership degree of belonging for all magnitudes and distance will be also constant.

The second model which is used for predicting ground motions is proposed by Cheng, et al. [33]:

$$\widetilde{lnPGA} = -3.25 + 1.075\tilde{M} - 1.723\ \ln(\tilde{R} + 0.156\ e^{0.62391\ \tilde{M}}) \tag{9}$$

The standard deviation for this model is 0.577.

Another model for predicting ground motions is given by Wu, et al. [34]:

$$\widetilde{lnPGA} = 2.303 * 0.00215 + 0.581\tilde{M} - \log\left(\tilde{R} + 0.00871\ * 10^{0.5\,\tilde{M}}\right) - 0.00414\tilde{R} \tag{10}$$

For this model, the standard deviation is equal to 0.79.

Further, models are utilized to generate seismic hazard curve [2] which represent the relationship between annual exceedance rate and ground motion level.

Since the natural logarithm of PGA was normally distributed and the fuzzy probability of exceeding any PGA level is estimated by using fuzzy mean and standard deviation:

$$\tilde{P}(PGA > x|m,r) = 1 - \Phi(\frac{\ln x - \widetilde{lnPGA}}{\sigma_{\ln PGA}}) \tag{11}$$

4 A CASE STUDY IN YUNNAN PROVINCE, CHINA

4.1 Historical earthquake data for Yunnan Province, China

Due to the specific geographic location and climate complexity, China has been affected by different catastrophic events [35]. Some of the major disasters in China are floods [36-39], droughts [40-42], earthquakes [43, 44], typhoons [45-47], landslides [48-51] and others. The center of droughts, floods, typhoons and landslides is identified in central, southern, southwest and southeast areas of China [50].

China is prone to earthquakes [52] and it has the most severe seismic disasters in the world since it is located between the two large seismic zones, the Circum-Pacific and the Himalaya-Mediterranean seismic zones [53]. The frequency of occurrence of severe earthquakes is about 1/3 and the loss of lives is about 1/2 of the whole world [53].

Yunnan province is situated in the far southwest of China, its land covers area of approximately 394,000 square kilometers and it has a population about 45.7 millions. It is a mountainous area with high elevations in the northwest and low elevations in the southeast. The Province borders provinces Sichuan to the north, Guizhou to the northeast, Guangxi to the east, and countries, Vietnam to the southeast, Laos to the south, and Myanmar to the west (Figure 4). Kunming is the capital and the largest city in Yunnan Province.

Yunnan province is known for high seismicity (Figure 5). The Yunnan-Burma active block region is located south and east of the Himalayan syntax. It includes western Yunnan province [52]. It is an earthquake-prone region. The block region consists of the West Yunnan and the South Yunnan blocks. The Langcang River-Nu River fault zone shows very strong seismic activity.

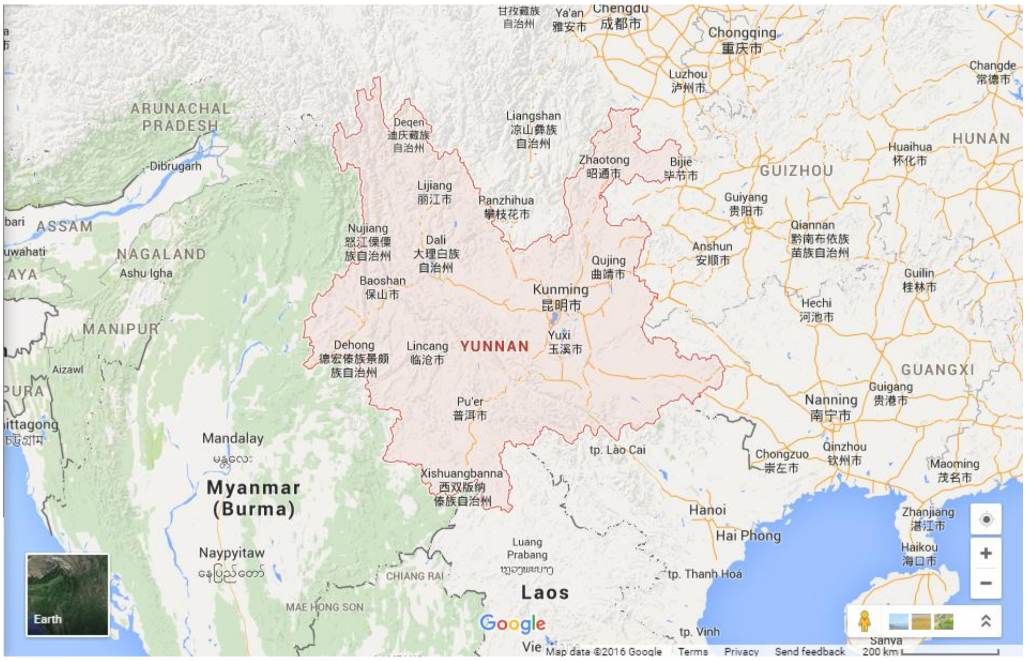

Figure 4 Location of Yunnan Province and neighboring Provinces and countries

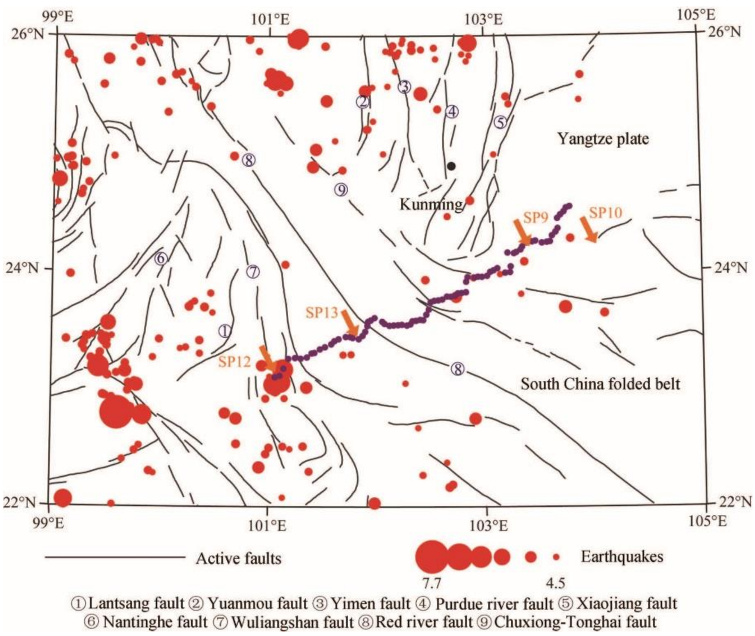

Figure 5 Active seismic faults in the Yunnan Province [54]

The PGA is estimated from using actual seismicity and ground motion models. The catalog includes 93 events, which are listed in Table 1 (Appendix A). The records are taken for the period of 100 years, between 1916 and 2015.

The estimated mean value and standard deviation are estimated from the probabilistic paper which is shown in Figure 6. The mean value of earthquake magnitude is 5.8 and the standard deviation is 0.8.

For this study, thresholds in this study are based on engineering judgment. A magnitude threshold (m_0) of 5.0 is selected. and a distance threshold (d_0) of 200 km are selected for this case study [31].

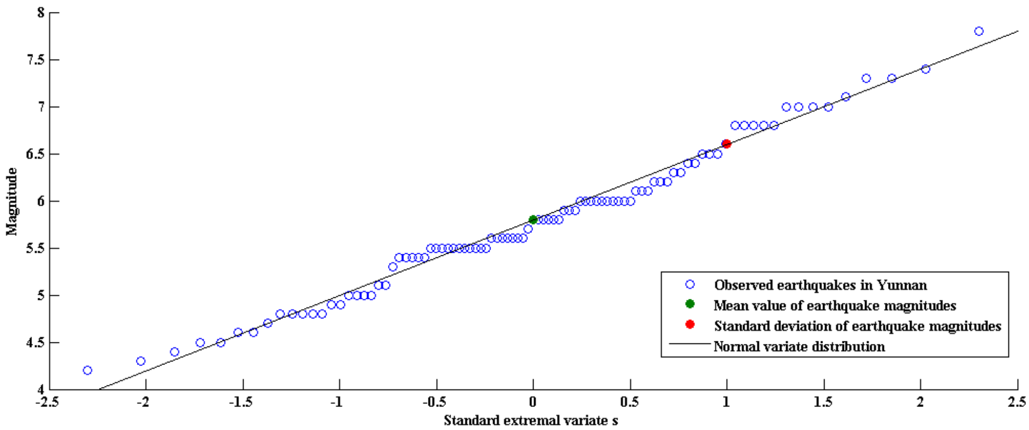

Figure 6 The probability paper for observed earthquakes in China, Yunnan Province

4.2 Results

The fuzzy-probability of exceedance of PGA level is determined for 10,000 earthquake scenarios. Earthquake scenarios have been simulated for earthquake magnitude which follows fuzzy-probabilistic distribution and the fault-distance prescribed in the Chapter 3. The earthquake magnitude follows normal distribution, which is determined in Chapter 3.2 for Yunnan Province. Further, the earthquake magnitude has been fuzzified according to the equation (9). The hazard curves are depicted in Figure 7. On this graph, the x-axis illustrates the level of PGA which takes values from 0 to 1.5 g. On the y-axis, the probability of exceedance the certain level of PGA for each hazard curve is denoted with the membership degree.

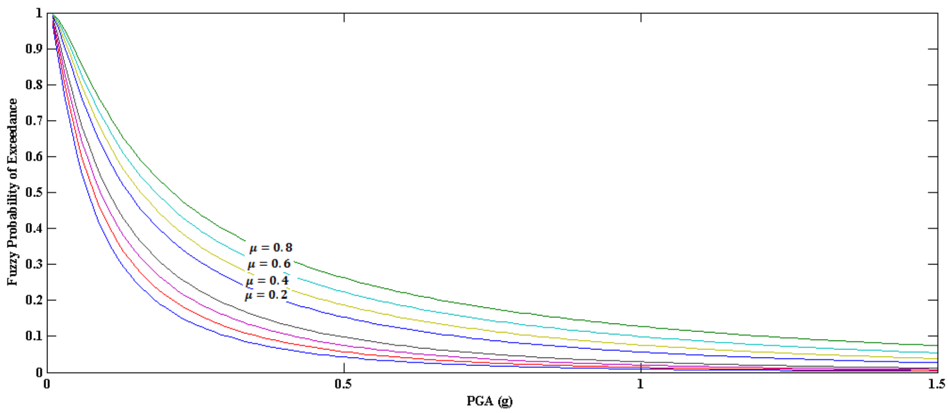

Figure 7 Hazard curve in terms of fuzzy probability for Yunnan Province, China

5 CONCLUSION

This paper introduces the model for the seismic hazard analysis based on the fuzzy-probabilistic approach. In this model, the earthquake magnitude and the source-to-site distance are defined as fuzzy sets. In comparison with other models, fuzzy triangular numbers are more suitable to represent the parameters of the seismic hazard since they include epistemic uncertainty in the seismic risk assessment. Further, FPSHA enables to evaluate the seismic risk more precisely and to assign the corresponding membership functions to each curve of the seismic hazard. In this paper, it is shown that fuzzy sets could help to integrate all the uncertainties which occur in the process of seismic hazard analysis.

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Appendix A: The historical earthquake data for Yunnan Province, China

Year	Earthquake magnitude
1917	6.8
1918	5.5
1925	7
1925	5.8
1926	5.5
1927	6
1927	5
1927	5.5
1930	6
1930	6.5
1934	6
1936	5.5
1938	6
1939	5.5
1940	6
1940	5.5
1941	7
1941	7
1942	6.8
1947	5.5
1948	6.8
1950	7
1950	5.8
1951	6.3
1952	6.5
1952	5.8

1953	5
1955	6
1955	6.8
1961	5.8
1961	6
1962	5.5
1962	6.2
1963	6
1964	5.4
1965	6.1
1966	5.1
1966	6.5
1966	6.2
1966	5.4
1966	6.4
1970	7.8
1974	7.1
1976	7.3
1976	7.4
1985	5.8
1988	7.3
1988	6.4
1989	5.6
1993	5.6
1995	6.8
1995	6.2
1996	6.6
1998	4.5
1999	4.6
2000	5.9
2000	6.3
2000	4.2
2001	5.5
2001	4.3
2001	5.6
2003	5.9
2003	5.6
2003	5.6
2003	4.7
2004	5.4
2004	4.4
2005	4.8
2005	4.8

2005	4.5
2007	6.1
2008	5
2008	6
2008	4.8
2009	5.7
2009	4.9
2010	4.8
2011	4.8
2011	5.5
2011	5.3
2011	5
2012	5.5
2012	5.6
2013	4.9
2013	5.4
2013	5.8
2014	5.4
2014	5.9
2014	6.1
2014	5.1
2014	6
2014	5.6
2015	4.6

Table 1 Historical earthquake data (1916-2015) for Yunnan Province in China

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