Development of Probabilistic–Fuzzy Model for Seismic Hazard Analysis

지진예측을 위한 확률론적퍼지모형의 개발

홍　　갑　　표*
Hong, Kappyo

ABSTRACT

A probabilistic–Fuzzy model for seismic hazard analysis is developed. The proposed model is able to reproduce both the randomness and the imprecision in conjunction with earthquake occurrences. Results of this research are (a) membership functions of both peak ground accelerations associated with a given probability of exceedance and probabilities of exceedance associated with a given peak ground acceleration, and (b) characteristic values of membership functions at each location of interest. The proposed probabilistic–fuzzy model for assessment of seismic hazard is successfully applied to the Wasatch Front Range in Utah in order to obtain the seismic maps for different annual probabilities of exceedance, different peak groud accelerations, and different time periods.

요　약

지진예측을 위한 확률론적퍼지모형을 제안하였다. 제안된 모형은 지진발생에 대하여 무작위성(randomness)과 퍼지니스(fuzziness)를 같이 사용하여, 기존의 확률론에 근거한 지진예측방법을 개선할 수 있도록 하였다. 이 연구의 결과는 (a) 주어진 초과확률에 대한 지반가속도 또는 주어진 지반가속도에 대한 초과확률의 멤버쉽함수와 (b) 멤버쉽함수를 대표할 수 있는 특성값(characteristic value)이다. 확률론적퍼지모형을 미국 Utah주의 Wasatch Front Range의 자료에 적용하여 서로 다른 연간초과확률, 최대지반가속도에 대하여 지진도를 작성하였다.

INTRODUCTION

Even though deterministic methods for seismic hazard analysis are still used by many engineers, most of the earthquake occurrence models currently in use are based on the probabilistic Poisson model (i.e., time–independent model), which assumes a memoryless property of seismic occurrences. Cornell's original work [9] on the time–independent model proposed in 1968, also called the point–source model, and his subsequent pioneering efforts

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* 공학박사, 연세대학교 건축공학과

이 논문은 1990년도 한국과학재단의 신진연구비에 의하여 연구되었음.

이 논문에 대한 토론을 1991년 12월 31일까지 본 학회에 보내주시면 1992년 6월호에 그 결과를 게재하겠습니다.

with Vanmarcke [10], can be considered as the beginning of application of probabilistic concepts to time-independent seismic hazard prediction. Point-source models are based on the assumption that the energy released during an earthquake is radiated from the focus and the intensity of the site ground motion is a function of the distance to the source. Although this assumption may be acceptable for certain earthquakes and regions, it would not, however, be valid for large events where the total energy released is distributed along a rupture zone. The "fault-rupture model" developed by Der Kiureghian and Ang in 1977 [11] is based on the assumptions that the earthquake originates at the focus and propagates symmetrically on each side of the foucs along a fault, and the maximum intensity of the ground shaking at a site is determined by the rupture that is closest to the site. Bender[2] further developed a "finite-fault rupture model" assuming that the entire rupture must be contained within the fault.

Although the Poisson model provides an adequate description for some seismic regions, time-dependent models have recently been developed. These models are based on the observation that the size of and the elapsed time since the last major earthqake are positively correlated. In 1984, Kiremidjian and Anagnos [19] developed the stochastic slip-predictable model for the estimation of earthquake occurrences based on the premise that strain energy accumlates along a fault and is released during an earthquake event. In this model, the temporal dependence of events is presented through semi-Markovian modeling of the sequence of earthquake occurrences.

In order to improve probabilistic analysis models, several attempts have been made acknowledging the fact that seismic hazard for the same site is quite different depending on the experts and uncertainties they consider. The Yankee Atomic Electric Company methodology employed a logic tree approach to model the uncertainty [22]. In the Lawrence Livermore National Laboratory methodology [21], the zonation and estimation of the parameters of the recurrence model were selected by experts, and a multi-method approach was used for determining site specific spectra for Eastern United States based on the opinions of ground motion experts. The methodology proposed in [21] encompasses a probabilistic approach for predicting peak acceleration, peak velocity and uniform hazard spectra for different time periods, and an empirical approach which includes the calculation of 50th and 84th percentile spectra from ensembles of real data at different magnitudes, site conditions, and distance ranges. Modeling uncertainties were introduced using alternative zonations and/or models as well as ranges of values for the seismicity parameters. These uncertainties were modeled in terms of probability distributions which were sampled, using Monte Carlo simulation, to describe the resulting uncertainty in the estimation of seismic hazard. In the Electric Power Research Institute seismic hazard methodology [14], the logic tree approach was applied to model the uncertainty using input provided by six seismicity teams. In this methodology, no attempt was made to model the uncertainty in the groud motion and only few equally weighted ground motion models were used to develop representative interim results.

Fuzzy mathematics was applied to seismic hazard by Lammarre and Dong [20], among others. In this methodology, the knowledge necessary to perform this task is extracted from experts' opinions using questionaires combining various factors involved in a seismic hazard assessment, such as ground motion, soil condition, and ground failure potential. Combination functions are then selected to reproduce the experts' opinions, and fuzzy sets theory (using vertex method) is used to combine the vague information to get a total evaluation of the seismic hazard for a given location.

In this paper, probabilistic time-independent models and fuzzy sets theory are combined in an original probabilistic-fuzzy approach to seismic hazard analysis. The proposed approach is able to reproduce both the randomness and the imprecision in conjunction with earthquake occurrences. Results of this research are (a) membership functions of both peak ground accelerations associated with a given probability of exceedance and probabilities of exceedance associated with a given peak ground acceleration, and (b) characteristic values of membership functions at each location of interest. The proposed probabilistic-fuzzy model for assessment of seismic hazard is successfully applied to the Wasatch Front Range in Utah in order to obtain the seismic maps for different annual probabilities of exceedance, different peak ground accelerations, and different time periods.

PROBABILISTIC-FUZZY APPROACH

The general seismic hazard analysis (SHA) process for an individual site requires four steps : (a) source modeling (e.g., point, line or area sources), (b) magnitude-frequency relationship, (c) attenuation law, and (d) evaluation of the probability of exceeding a given ground motion level (often peak ground acceleration) within a specified exposure time (often annual). Presently, there are four ways by which the SHA is conducted : (a) using local codes : (b) using a deterministic seismic hazard evaluation : (c) using a probabilistic hazard evaluation : and (d) using a Bayesian seismic hazard evaluation. The advantages and disadvantages of each of these approaches have been summarized by Hong [17] who pointed out that fuzzy sets theory could be used in order to conduct SHA. There are large uncertainties associated with each step of the SHA process. In general, these uncertainties are distinctive : irreducible (i.e., randomness) and reducible (i.e., fuzziness). Randomness is a variability that is inherent to the unpredictable nature of future earthquakes and is beyond our control, while fuzziness can be attributed to incompleteness of statistical data (i.e., estimation error), model imperfection e., lack of understanding), and differences of opinion among experts. Expert opinions often play a key role in each step of seismic risk analysis, resulting in personal biases and some arbitrariness. Usually the expert opinion is vague, consisting mostly of language descriptions. Hence a method which include the subjective opinion is needed in order to infer the final results from that information. In this paper, fuzzy sets theory is combined with probability theory in order to include the subjective opinion.

Fuzzy sets theory, proposed by Zadeh in 1965 [23], deals with the subjective uncertainty factors in a quantitative way. The concept of fuzzy probability is particularly useful in the derivation of a new method of analysis in which the subjective information given by experts is integrated through the membership function instead of correction factors in the calculation of seismic risk. The theory of fuzzy sets deals with a subset A of the possibility space X, also termed the universe of discourse, where the transition between full membership and no membership is gradual rather than abrupt. The fuzzy subset A has no well-defined boundaries in the possibility space X which covers a definite range of objects. Fuzzy classes of objects are often encountered in the real world. For instance, A may be the set of "enough earthquake data" in a region X. Traditionally, the grade of membership 1 is assigned to those objects that fully and completely belong to A, while 0 is assigned to objects that do not belong to A at all. The more an object x belongs to A, the closer to 1 is its grade of membership $\mu_A(x)$ in fuzzy sets theory.

Consider an example problem of application of probabilistic fuzzy approach to seismic hazard analysis. A line source symmetirc with respect to a site is considered. For this source the following assumptions are made: the maximum magnitude $m_{\max}$ is 8: the shortest fault-to-site distance r_0 is 20km: the length of the falut ℓ is 500km: the Donovan's attenuation function [13] is used: the slope for the Gutenberg-Richter's law of magnitude is prescribed: and the slip-length relationship is given according to Bonilla and Buchanan [4]. In this example problem, the maximum magnitude, M_{max}, the shortest distance to the fault, R_o, and the length of fault, L, are assumed as fuzzy variables with the follwoing membership functions:

$$\mu M_{max}(m) = 0.0 \mid 7.5 + .36 \mid 7.6 + .64 \mid 7.7 + .84 \mid 7.8 + .96 \mid 7.9 + 1.0 \mid 8.0 + .96 \mid 8.1 + .84 \mid 8.2 + .64 \mid 8.3 + .36 \mid 8.4 + 0.0 \mid 8.5 \quad (1)$$

$$\mu_{R_0}(ro) = 0.0 \mid 16 + .5 \mid 17 + 1.0 \mid 18 + .83 \mid 19 + .67 \mid 20 + .5 \mid 21 + .33 \mid 22 + .17 \mid 23 + 0.0 \mid 24 \quad (2)$$

$$\mu_L(\ell) = 0.0 \mid 450 + .33 \mid 467 + .67 \mid 483 + 1.0 \mid 500 + .67 \mid 517 + .33 \mid 533 + 0.0 \mid 550 \quad (3)$$

in which 0.0/7.5 means that the membership of $M_{max} = 7.5$ is 0, and 0.36 |7.6 means that the membership of $M_{max} = 7.6$ is 0.36.

The extension principle has been applied to this problem along with the computer program SEISRISK Ⅱ developed by Bender and Perkins [3] for obtaining two different types of membership functions: (a) Type 1-membership function of peak groud acceleration given the annual probability of exceedance, and (b) Type 2- -membership function of annual probability of exceedance given the peak ground acceleration. Results for such membership functions are given in Hong[17], Frangopol, Ikejima and Hong [15], Frangopol and Hong [16], and Hong and Frangopol [18].

Two computer programs have been developed by Hong [17] for SHA using a probabilistic-fuzzy approach. The first program is based on the extension principle and the second on the vertex method. Using (a) the subjective input from expert opinions represented by the membership functions of fuzzy variables (i.e., maximum magnitude, fault length, distance to the fault), (b) the random uncertainties in the parameters of the Bender-Perkins model, and (c) the program SEISRISK Ⅱ, the two computer programs developed by Hong use fuzzy integration in order to find the characteristic values of membership functions (e.g., peak ground acceleration given the annual probability of exceedance) at each location of interest.

APPLICATION TO UTAH AREA

In this section, the probabilistic–fuzzy approach briefly presented previously is applied to the Wasatch fault zone in Utach in order to obtain the seismic map from 37°N latitude, southernmost of Utah, to 42°N latitude, northernmost of Utah, and from 114°W logitude, westernmost of Utach, to 109°W longitude, easternmost of Utah.

The fifteen seismic souce zones considered are based on the national map of Algermissen et al. [1]. Strong–motion data recorded within 50km of the rupture zone were used to develop the attenuation characteristics of horizontal peak ground acceleration for worldwide earthquakes of magnitudes 5.0 to 7.7 The data provided by the U.S. Geological Survey, Golden, Colorado, had been used for the near–source attenuation relationships in terms of earthquake magnitude, source–to–site distance, and several source and site parameters in northcentral Utah [7]. The data base consists of 134 horizontal components of peak ground acceleration recorded from 21 earthquakes. From the total of 134 records, 129 earthquakes are used in this research including only earthquakes in California, acknowledging that the tectonics and recording practices at other sites (Nicaragua, Hawaii, U.S.S.R., Iran and Alaska) may be substantially different from those in the Western United States. It is also acknowledged that reducing the number of data may reduce the credibility of statistical data. However, the total number of earthquake data is outweighed by the consideration of uncertainties residing behind the data, such as the accruacy of recordings, different geology conditions, and different tectonics.

For an earthquake occuring randomly within a source the attenuation relationship

$$Y=c_1\, e^{c2\,M}\,(R+25)^{-Cs} \tag{4}$$

is used where Y represents the mean of the peak acceleration scaled from the two horizontal components of each acceleration recording, M is the earthquake magnitude, R is source–to–site distance, and c_1, c_2 and c_3 are regression coefficients which are correlated with each other though the data provided. In order to obtain the membership functions of the coefficients c_1, c_2 and c_3, a membership function is assumed for the coefficient c_2. The membersip function of the coefficient c_2 shown in Fig. 1(a) was

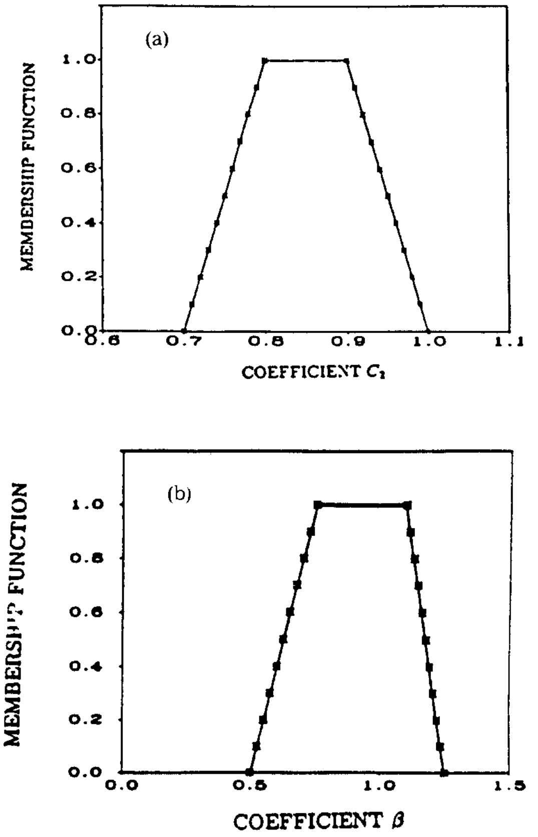


Figure 1. Membership functions of coefficients c_2 and β.

suggested by researchers from the U.S.Geological Survey, Golden, Colorado. The membership functions of the coefficients c_1 and c_3 were obtained by applying regression analysis to the 129 available earthquake recordings [17].

Similar to the derivation of the membership functions of the coefficients c_1, c_2 and c_3 in the attenuation relation (4), a membership function is assigned to the coefficient β in the magnitude-frequency relation

$$\ell_n \mathrm{N}(m) = \alpha - \beta M \tag{5}$$

and, using regression analysis, the membership function of the coefficient α is found [17]. In Eq. 5, $N(m)$ is the number of earthquakes in a given time period (e.g., annual) having magnitudes greater than m. The membership function of the coefficient β, shown in Fig. 1(b) was provided by researchers from the U.S. Geological Survey, Golden, Colorado.

An estimation of maximum magnitude M_{max} of earthquakes for each seismic source of interest is needed for probabilistic seismic risk analysis. Typically, maximum magnitudes are estimated in the Western United States based on assessments of various fault characteristics, such as rupture length, total length, maximum displacement event, rupture area, and seismic moment. Assessment of maximum magnitude in the Central and Eastern United States are difficult because of the uncertainties involved in associating earthquakes with faults. The methods most commonly used to estimate maximum magnitudes in Eastern United States are as follows [8]: (a) addition of an increment to the largest historical magnitude; (b) extrapolation of normalized frequency-magnitude recurrence curves to "rare" evnets such as 100 year event: (c) statistical treatment of seismicity data: and (d) analogy to other seismic sources or other regions of similar tectonic characteristics. In this study, membership function for the maximum magnitude is assumed, based on addition of an increment (i.e., 1.0) to the largest historical magnitude, as follows

$$\begin{aligned}
&\mu M_{max}(m) = 0 && \text{if } M < M_{h,\,max} \\
&\mu M_{max}(m) = 1 && \text{if } M_{h,\,max} \le M < M_{h,\,max} + 0.5 \\
&\mu M_{max}(m) = 1 - 2 && (M - (M_{h,\,max} + 0.5)) \qquad (6) \\
& && \textit{if } M_{h,\,max} + 0.5 \le M < M_{h,\,max} + 1 \\
&\mu M_{max}(m) = 0 && \text{if } M > M_{h,\,max} + 1
\end{aligned}$$

where $M_{h,\,max}$ is the largest historical magnitude. The largest historical magnitude for each of the 15 zones considered in this study is given n [17].

Using as input the membership functions of (a) the ccoefficients c_1, c_2 and c_3 in Eq. 4, (b) the coefficients α and β in Eq. 5, and (c) the maximum magnitudes of earthquakes associated with the 15 zones considered in this study, a probabilistic-fuzzy computational procedure was developed to calcualte the membership functions of both the probability of exceedance and the peak ground acceleration (PGA) for the entire Utah area. The main steps of this procedure, involving α-cut method, vertex method, probabilistic seismic risk analysis (i.e., SEISRISK II program), extension principle, and fuzzy integration are summarized in Fig. 2. The reader is referred to Zadeh [23], Brown [5], Brown and Yao [6], Dong, Shah and Wong [12], and Hong [17], among others, for a comprehensive treatmemt of fuzzy computation methods. For the entire Utah area, Figs. 3 (a)-(c) show examples of maps of probability of exceedance and peak ground acceleration. More examples of such 3-D maps have been produced by Hong [17] for different probabilities of exceedance, different peak ground accelerations, and different time periods.

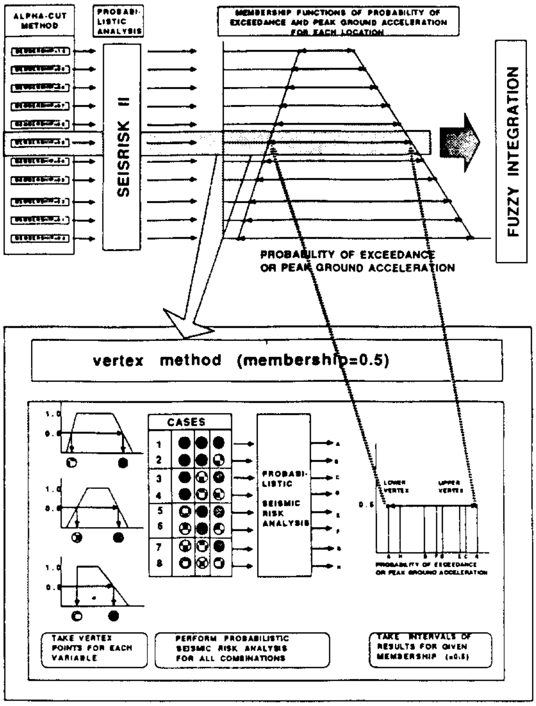
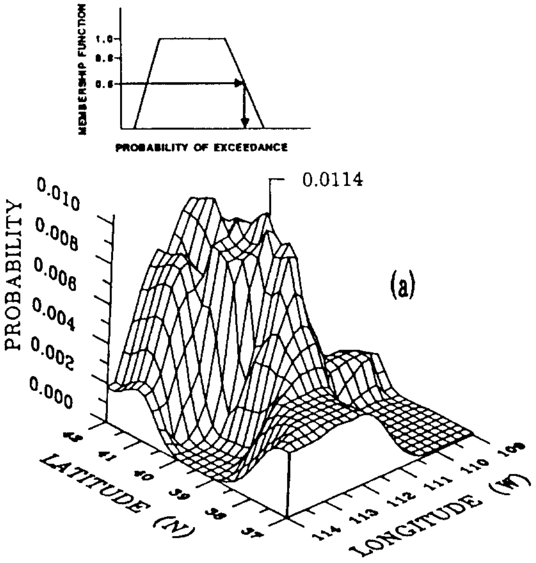
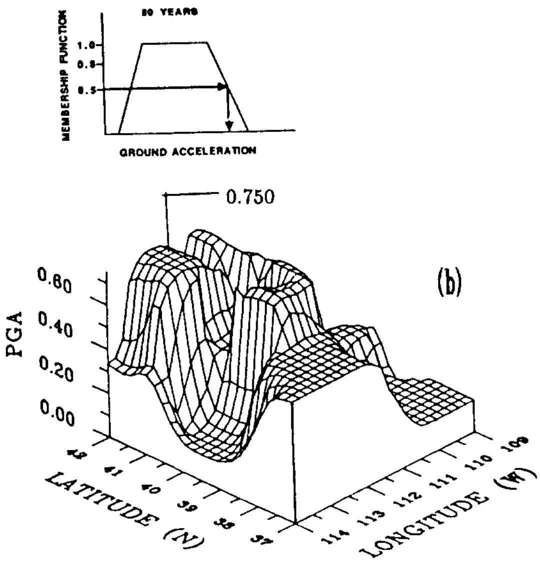


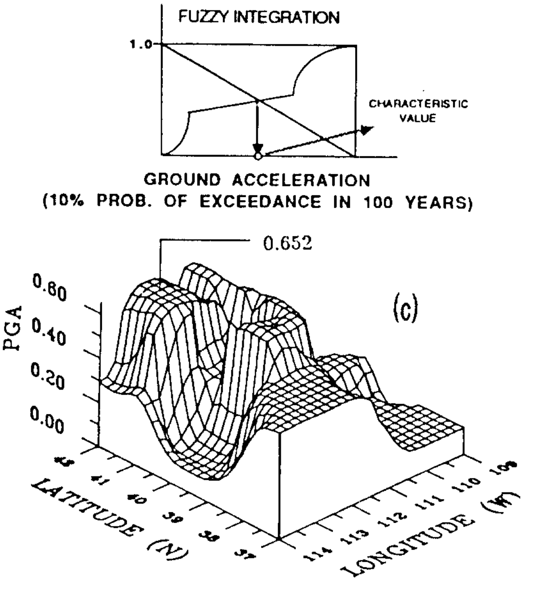
Figure 2. Schematic diagram of the probabilistic-fuzzy approach for Utah area.



(a)



(b)



(c)

Figure 3. 3D maps of the Utah area for (a) the annual probability of exceedance of 0.2 PGA, (b) PGA for 10% probability of exceedance in 50 years, and (c) characteristic PGA for 10% probability of exceedance in 100 years.

CONCLUSIONS

Some specific comments and recommendations on seismic hazard assessment, with particular reference to fuzzy sets applications, may be derived from the results presented in this study.

1. The results presented indicte the feasibility of using fuzzy sets theory in assessing the seismic hazard. By using this novel theory, seismic hazard is predicted in terms of membership values of both ground accelerations and exceedance probabilities. This approach to predict seismic hazard appears more rational than the current prediction models which use conventional probabilistic methods and do not generally include uncertainties associated with incompleteness of information and knowledge.
2. It is seen from the examples presented that an important factor influencing the seismic hazard prediction is the choice of the input membership functions for the attenuation and magnitude–frequency relations. Another important factor is the choice of the membership function of the maximum magnitude.
3. The probabilistic–fuzzy computation of seismic risk for any membership value and its incorporation in a seismic hazard map, should stimulate studies of both random and fuzzy variables encountered in earthquake prediction to improve their description. In this context, empirical studies are needed to determine reasonable membership values for fuzzy variables associated with earthquake prediction.
4. The area of earthquake engineering applications of fuzzy sets theory is not as well developed to date as that of probability theory. More investigations are needed to extend and implement the probabilistic–fuzzy approach for seismic hazard proposed herein. Further research is needed to extend this model to time–dependent earthquakes and to combine experts' opinions in a consistent manner. Also, for implementation of the proposed model general seismic risk analysis computer programs using both probabilistic and fuzzy information will be needed.

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(접수일자 : 1991.7.5)