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New fuzzy method in choosing Ground Motion Prediction Equation (GMPE) in probabilistic seismic hazard analysis

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Abstract. Recently, seismic hazard analysis has become a very significant issue. New systems and available data have been also developed that could help scientists to explain the earthquakes phenomena and its physics. Scientists have begun to accept the role of uncertainty in earthquake issues and seismic hazard analysis. However, handling the existing uncertainty is still an important problem and lack of data causes difficulties in precisely quantifying uncertainty. Ground Motion Prediction Equation (GMPE) values are usually obtained in a statistical method: regression analysis. Each of these GMPEs uses the preliminary data of the selected earthquake. In this paper, a new fuzzy method was proposed to select suitable GMPE at every intensity (earthquake magnitude) and distance (site distance to fault) according to preliminary data aggregation in their area using α cut. The results showed that the use of this method as a GMPE could make a significant difference in probabilistic seismic hazard analysis (PSHA) results instead of selecting one equation or using logic tree. Also, a practical example of this new method was described in Iran as one of the world's earthquake-prone areas.

Keywords: probabilistic seismic hazard analysis (PSHA); Ground Motion Prediction Equation (GMPE); fuzzy method; α cut

1. Introduction

Today, due to the irreparable disasters and events that have occurred as a result of earthquakes in the world which has caused incredible loss of life and property (Kappos *et al*. 2010, Kyriazis *et al*. 2011), there is not a slightest doubt about the importance of investigating earthquake and the dangers thereof. It is an undeniable truth that, according to the current knowledge of human, earthquake resistant design of structures and retrofitting existing structures are the only ways for dealing with this natural disaster. Undoubtedly, the first step is to analyze and evaluate the risks of earthquake and obtain a good estimate of the earthquake forces. In other words, all these facts demonstrate the importance of research about the analysis and evaluation of earthquake risk.

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Complexity of natural phenomena in general and earthquake in particular has caused inability in terms of their control and impossibility in defining the location and magnitude of future earthquakes based on the current knowledge.

In such cases, the use of statistics and probability is the only option for analyzing the phenomena. By combining the concepts of seismic geotechnical studies with probability, probabilistic seismic hazard analysis (PSHA) has emerged as the most common, complete, and the best method for seismic hazard assessment. More investigations are described in detail in some publications, such as the Earthquake Engineering Research Institute 1989.

Using this method, the uncertainty of various parameters can be considered and any changes in the earthquake location and magnitude can be properly affected.

The purpose of PSHA is to make a reasonable estimate of the probability of the parameters related to the movement of the earth in a specific site.

One of the most important parameters in PSHA is the ground-motion prediction equation (GMPE), which is used to estimate the ground-motion value for an earthquake, given the magnitude, distance, and site conditions. An appropriate attenuation equation not only can help to understand the characteristics of ground-motion attenuation, but can also predict the ground-motion values for a site so that earthquake-resistant structures can be appropriately designed.

Various studies on GMPEs have already been done in different districts (Joyner and Boore 1981, Jayaram *et al*. 2011, Vacareanu *et al*. 2014, Cheng *et al*. 2014) as well as in Iran (Zare 1999, Nowroozi 2005, Ghodrati 2007). However, there are big differences in the results of GMPEs, caused by various applied datasets (Abrahamson and Shedlock 1997). Also, the comprehensive summary of various equations was prepared by Douglas 2011.

Fuzzy logic, however, suggests significant advantages over this type of approaches because of its ability to generally represent the qualitative facets of analysis data and apply adjustable inference rules (Sun *et al*. 2002). Given the importance of GMPE and the dramatic impact on the final result of the earthquake risk analysis, selecting the appropriate equation in PSHA is the most important factor and numerous works have been conducted in this field. The most common method for selecting and mixing the appropriate equation is logic tree.

Kulkarni *et al*. (1984) first introduced the logic tree in PSHA as a tool to capture and quantify the uncertainties related to PSHA such as choosing appropriate GMPEs.

A logic tree in PSHA is described as the one in which all steps in seismic hazard analysis that have uncertainties are separated into branches, each branch is added to each of the choices considered feasible by the analysts, and a normalized weight is assigned to each branch.

The first step in logic tree method is to choose the appropriate relations for the studied area. Afterwards, a number between 0 and1has to be assigned to every relation, which is called normalized weight number, and reflects the analysis confidence in the choice of the most correct relation. The hazard calculation is then performed following all the possible branches. However, this method has two major weaknesses.

First, for assigning weight for each of the selected attenuation relations, a specialist's opinion is needed; so, many conflicts and errors can occur.

Second, each of the selected relations in this method will have a similar impact on all intensities (earthquake intensities) and distances (fault to site distances); i.e., if the normalized weight for the GMPE No. "1" is 0.3, it means that specialist's trust in that relationship is 30% and it is similar for all the intensities and distances. It is known, every relation has its own preliminary data and, based on the initial data used to create a relation, some of the magnitudes and distances have greater participation in the regression and creation of relations. So, for obtaining accurate results, it is necessary to avoid using one normalized weight for all the magnitudes and distances in one GMPE.

Fuzzy logic methods have been used in earthquake engineering to calculate seismic hazard (Lamarre and Dong 1986), to evaluate damage (Souflis and Grivas 1986), to obtain seismic response of building frames with MR dampers (Das 2012), to evaluate the uncertainties in structural systems and the following response by reason of ground motions (Wadia-Fascetti and Smith 1996). Lately it has been used to obtain earthquake response spectra systems (Wadia-Fascetti and Gunes 2000), to develop structural vibrations due to earthquakes (Nomura, Furuta and Hirokane 2007), to handle seismic vibrations of small-scale structures (Kim *et al*. 2010) and to derive ground motion equations for strong motion earthquake (Ahumada *et al*. 2012). The method presented in this study created a fuzzy attenuation values for each earthquake intensity and fault to site distance based on the preliminary data aggregation at every intensity and distance of chosen GMPEs. In fact in this method, based on the GMPE database, selecting one equation is not going to be trustworthy for every magnitude and distance; but, the appropriate fuzzy equation will be chosen for each of the magnitudes and distances.

2. Research direction

Since most of GMPEs using statistical regression techniques are obtained from the initial input database, the power and accuracy of the relation are within specific intensities and distances with greater participation in the initial data.

Parts of the equation results, in which the initial data are small, have low accuracy. Therefore, the criterion of accuracy in this method at every magnitude (M_w) and distance (focal distance) is their aggregation in the preliminary data.

So, in this new method, for each intensity and distance, an attenuation relation was selected which has the highest number of initial data in that area.

2.1 Degree of Membership (DOM) of distance (Fault to Site Distance)

In this phase, degree of membership of distances**,** according to the input database of each relationship, is separately calculated.

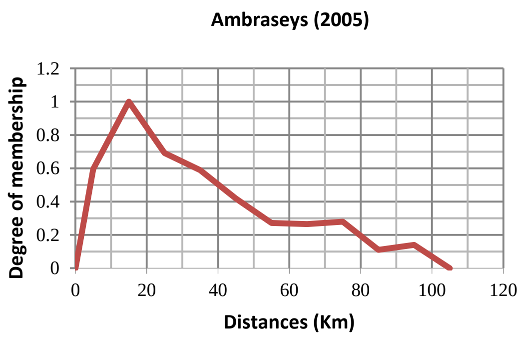

Fig. 1 Cumulative diagram for distances (fault to site distances) in Ambraseys' (2005) GMPE

Table 1 Cumulative values for distances (fault to site distances) in Ambraseys' (2005) GMPE

Ambraseys (2005)		
Distance Range	No. of Data	Degree of membership
0 Km - 10 Km	81	0.60
10 Km - 20 Km	136	1.00
20 Km -30 Km	94	0.69
30 Km - 40 Km	80	0.59
40 Km - 50 Km	57	0.42
50 Km - 60 Km	37	0.26
60Km - 70 Km	36	0.26
70Km - 80 Km	38	0.28
80 Km -90 Km	15	0.11
90 Km - 100 Km	19	0.14
100 Km - 110 Km	0	0.00

Table 2 Cumulative values for earthquake magnitude in Ambraseys' (2005) GMPE

Magnitude Range(Mw)	No. of Data	Degree of membership
4.5-5	0	0.00
5-5.5	187	1.00
5.5-6	165	0.88
6-6.5	109	0.58
6.5-7	87	0.47
7-7.5	25	0.13
7.5-8	20	0.11
8-8.5	0	0.00

Interval distance of 10 km is selected and, given the number of input data in each interval, the aggregation number is assigned. Then, all values are divided by the maximum aggregation number to obtain the normalized weight (DOM) for the distance. For example, DOM of Ambraseys' (2005) GMPE are shown in Table 1 and Fig. 1.

As can be seen in the above chart, most data in Ambraseys' (2005) GMPE range from 10 to 20 km; i.e., the highest level of reliability to this relation from the distance point of view is in this range. Also, at the distances of more than 110 km, this relation is slightly reliable.

2.2 Degree of membership of earthquake magnitude

In this phase, degree of membership (DOM) of earthquake magnitude, according to the input database of each relationship, is separately calculated. Interval magnitude of Δ m=0.5 is selected and, given the number of input data in each interval, the aggregation number is assigned. Then, all the values are divided by the maximum aggregation number to obtain the normalized weight (DOM) for the earthquake intensity. For example, tables and graphs of Ambraseys' (2005) equation shown in Table 2.

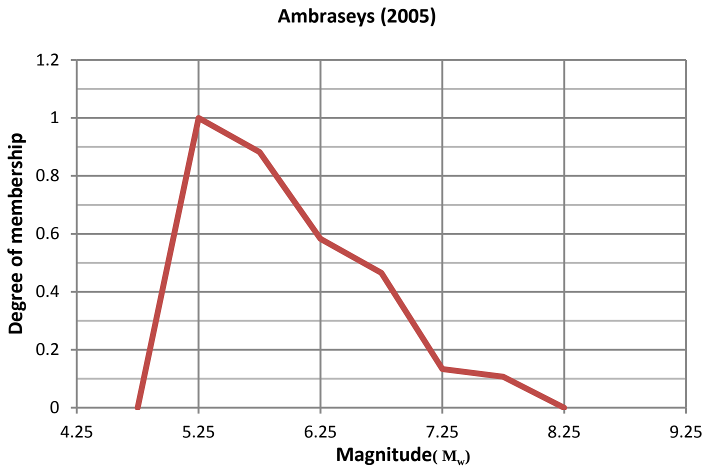

Fig. 2 Cumulative diagram for earthquake magnitude in Ambraseys' (2005) GMPE

As can be seen in the above chart, most data in the Ambraseys' (2005) equation range from the magnitude of 5 to 5.5; i.e., the highest level of reliability to this relationship from the magnitude point of view is in this range. Also, it shows that, at the magnitude of more than 8.5 and less than 4.5, this relation is slightly reliable.

2.3 Degree of membership of earthquake magnitude and distance

At this stage, given the DOM particularly gained by each of the GMPEs, the final DOM of the specific magnitude and distance for every relationship will be obtained.

The reliability index of the magnitude and distance combination is the minimum normalized weight (intersection) of magnitude and distance. By assigning the minimum of two DOM, those combination of distance and magnitude which had large DOM in both cells, had greater impact on final result. If a GMPE had a large DOM in distance cell but its magnitude DOM was few, it meant that the reliability for this relation in that distance-magnitude cell was not good enough.

For example, the magnitude's DOM for Ambraseys' equation between the intensity range of 6-6.5 is 0.58, and DOM of distance for this relation between the distance range of 40 and 50 km is 0.42. So, the final DOM for this relationship in the magnitude of 6 to 6.5 and distance range between 40 and 50 km, is minimum of 0.58 and 0.42, i.e., 0.42. The DOM of zero meant that the GMPE for that specific period of distance-magnitude is less reliable compared to the others. (But it did not mean that it is totally unreliable).

For more details, the final normalized DOM of Ambraseys' GMPE shown in Table 3.

The same calculation should have been done for all of the chosen GMPEs for the studied area. The numbers (DOM) in each cell represent the power and precision of the relationship at that intensity and distance.

Then, for each magnitude and distance, n DOMs are obtained and each of them is related to one specific GMPE (n is the number of chosen equations).

So, for each cell, there are n PGAs and every PGA has a reliability index called DOM. Also,

Table 3 Final DOM for every magnitude-distance in Ambraseys' (2005) GMPE

Ambraseys	Distances	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
Magnitude	Magnitude Weight Distance Weight	0.6	1	0.69	0.59	0.42	0.26	0.26	0.28	0.11	0.14
4-4.5	0	0	0	0	0	0	0	0	0	0	0
4.5-5	0	0	0	0	0	0	0	0	0	0	0
5-5.5	1	0.6	1	0.69	0.59	0.42	0.27	0.27	0.28	0.11	0.14
5.5-6	0.88	0.6	0.88	0.69	0.59	0.42	0.27	0.27	0.28	0.11	0.14
6-6.5	0.57	0.57	0.57	0.57	0.57	0.42	0.27	0.27	0.28	0.11	0.14
6.5-7	0.46	0.46	0.46	0.46	0.46	0.42	0.27	0.27	0.28	0.11	0.14
7-7.5	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.11	0.13
7.5-8	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11

every magnitude and distance has its own fuzzy diagram. Then, using α cut method, the PGA range for every cell in various reliability index (DOM) is achieved.

It should be noted that there are several methods in assigning DOM of each M-R bin. One of these practical methods is to use both of magnitude and distance data together and the DOM of each M-R bin calculated directly by the number of data used in the M-R bin. The result of this method is not the same but is in the same direction with the presented method in this article. In presented method most of the bins (even those with zero probability of basic data in GMPE) has possibility to participate in algorithm with lower DOM and more M-R bins contribute in the calculation.

The final step in PSHA is to draw the hazard curve for the studied area. Using this method, PGA range is given at each magnitude and distance. So, in each DOM, there is a hazard surface as the final result.

Using this method, not only the relation weight, but also the magnitude-distance weight will affect the relationship selection.

3. Practical example for Tehran

Iran is located on one of the most seismic zones of the world. It is situated over the Himalayan-Alpied seismic belt and is one of those countries which have lost many human lives and money due to the occurrence of earthquakes. In this country, a destructive earthquake occurs every several years due to being situated over a seismic zone. Tehran as the capital city of Iran with the population of over 10 million people is known as an economic and political center. The probability of occurrence of a large earthquake (M>6.5) within a circular area of 150 km around Tehran, in the next 100 years, has estimated to be 0.65 (Yadman Sazeh Corporation 2002). Unfortunately, the sparse strong-motion data set presently available from existing faults in Tehran area makes the estimation of ground motion during future earthquakes quite a challenge. Tehran is close to the Mosha, North Tehran, North Ray, South Ray, Kahrizak, Garmsar and Pishva active reverse faults.

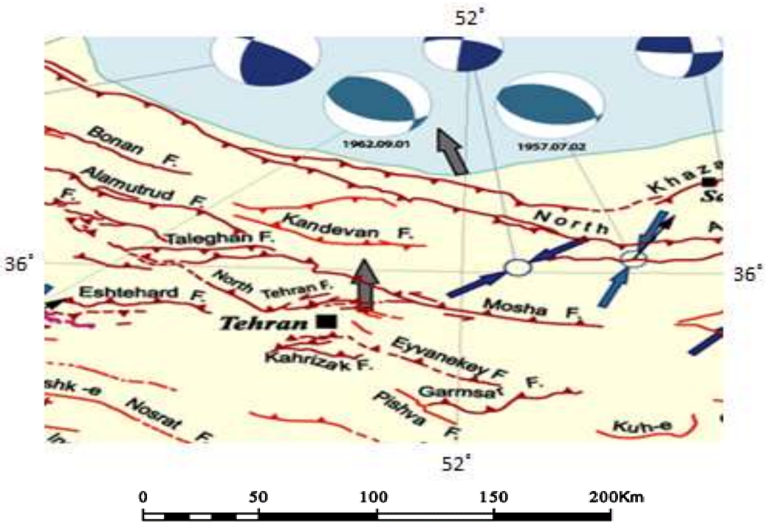

Fig. 3 The major faults surrounding Tehran

3.1 Seismic source characteristic of Tehran

Existence of active faults like North of Tehran, Mosha, and North and South of Ray along with strong earthquakes in the past indicates the great seismicity of this region and high probability of an earthquake with the magnitude of more than 6.5. The Mosha fault is over 200 km long, and consists of several segments. According to Berberian and Yeats (1999), at least three damaging historical earthquakes ruptured adjacent segments of the Mosha fault for a continuous distance of nearly 200 km: 958 (western segment), 1665 (eastern segment), and 1830 (central segment, north of Tehran). The North Ray and South Ray are located on the south border of Tehran city. The length of these faults is about 20 km. The North Tehran lies on the boundary between the northern mountainous area and the city area. This fault which extends over 75 km consists of two main segments: North-western and eastern parts (Berberian *et al*. 1983).

In this section, the probabilistic seismic hazard of Tehran is analyzed using the proposed method. Then, the result is compared with that of other equations and logic tree method. The three

Table 4 Characteristics of major faults in Tehran

No.	Fault	Length (km)	M_{max}
1	Mosha	200	7.5
2	N.Tehran	75	6.9
3	Niavaran	13	6
4	N-Ray	17	6.1
5	S-Ray	18.5	6.2
6	Kahrizak	40	6.6
7	Garmsar	70	6.9
8	Pishva	34	6.5

districts in Tehran with the following characteristics are selected.

• Abbasabad in the center of Tehran with longitude of 51.24 and latitude of 35.44,

• Shahrak-Laleh in the north-east of Tehran with longitude of 51.18 and latitude of 35.48, and

• Baghershahr in the South of Tehran with longitude of 51.23 and latitude of 35.31

Site: soil, 175 m/s<V_s<300 m/s

m_0 =4

$\lambda(4)=0.37$, $\beta=1.41$ (Tavakkoli)

$\lambda(4)=0.63$, $\beta=1.08$ (Ghodrati)

Style of faulting: Reverse

Source Type: Line Source

It should be noted that the used rate of earthquake activity (λ) was obtained by assigning the same weight value for each of above amounts (50% for Ghodrati "λ, β" value and 50% for Tavakkoli "λ, β" value). Also, for magnitude (M_l, M_s, M_b) conversion into M_w, Kanamori's (1983) graph was used.

For seismic risk analysis, a wide range of district between 50 and 53 longitudinal degrees and 35 and 36.5 latitudinal degrees was selected. All the seismic factors, i.e., faults in a way that may affect the range of the target, were detected.

The most important faults that can be detected in the range of target zone were listed in Table 4.

3.2 Probabilistic seismic hazard analysis of Tehran

In this study, based on Pacific Earthquake Engineering Research Center Report (2011), seven GMPEs were selected for Iran. According to the Iran local site conditions and soil characteristics it was reasonable to choose the most GMPEs from Iran. 3 practical and important relationships from central Iran was chosen (Ghodrati 2007, Zare 1999, Nowroozi 2003). To consider the other conditions and factors, other relations with a global credit and broader range of data should be selected too. Among which 2 were related to the Middle East (Ambraseys 2005, Bommer 2003), and 2 were worldwide (Sarma 1996, Graizer 2007).

1-Ghodrati 2007

2-Zare 1999

3-Nowroozi 2003

4-Ambraseys 2005

Table 5 DOMs of the GMPEs and their PGAs for magnitude range of 4.5 to 5 and distance range of 10 to 20 km

Relation Type	DOM	PGA (g)
Ghodrati	1.000	0.026
Graizer	0.525	0.033
Nowroozi	0.311	0.010
Bommer	0.173	0.025
sarma	0.148	0.045
Zare	0.112	0.016
Ambraseys	0.000	0.014

Table 6 PGA range of different GMPEs for magnitude range of 4.5 to 5 and distance range of 10 to 20 km

DOM	PGA Range (g)
1.000	0.026
0.525	0.026 - 0.033
0.311	0.01 - 0.033
0.173	0.01 - 0.034
0.148	0.01 - 0.045
0.112	0.01 - 0.045
0.000	0.01 - 0.045

5-Bommer 2003
6-Sarma 1996
7-Graizer 2007

For this example, the range of earthquake magnitude was between 4 and 8 with the magnitude interval of Δ m=0.5 and the fault to site distance ranged from zero to 120 km with the distance interval of 10 km.

Therefore, for each relationship, a matrix with 8 rows and 12 columns was formed. And, the normalized values entered for each cell were the final DOM for the specific magnitude and distance. So, for every distance and magnitude, there were 7 DOM, each related to one equation. For example, these values for magnitude ranged from 4.5 to 5 and distance of 10 to 20 km, are in Tables 5-7.

Then seven GMPE's sorted in descending order according to their DOM's. In the next step, starting from the largest DOM, PGA range will be formed due to the degree of their membership.

For example the PGA of Ghodrati GMPE with DOM of 1 is 0.026. The 2nd largest DOM is for Graizer GMPE and its PGA is 0.033. It showed that with the degree of membership of 0.525 the PGA range could be between 0.026-0.033. Likewise on the lower DOMs the PGA range increased or remained unchanged. So that at the lowest DOM between the chosen GMPEs the PGA range is 0-0.014. It meant that with the biggest possibility the PGA for magnitude ranged from 4.5 to 5 and distance of 10 to 20 km is 0.026 and as the DOM decreased the PGA range increased. (Table 6 and Fig. 4.)

One of the most practical method in defuzzification is α cut method.

An α-cut or α-level set of a fuzzy set $A \subseteq X$ is an ordinary set $A_\alpha \subseteq X$, such that

$$A_\alpha=\{\mu_A(x)\geq\alpha,\ \forall x\in X\} \tag{1}$$

For example the PGA range of DOM 0.7 is 0.026 - 0.031 as shown in Fig. 6.

For convenience in calculations instead of having various amount of DOM between 0 to 1, using α cut method, its period divided into 10 equal intervals. (Table 7)

Then, the rest of the steps for obtaining the final hazard curve by dividing the line source into 20 equal segments and using Eqs. (2)-(4) were followed

$$P(PGA > a \mid EQ) = \int_{Rmin}^{Rmax} \int_{m0}^{mmax} P(\, PGA > a \mid EQ\!: M, R\,) f(M) f(R) dM dR \tag{2}$$

$$P(PGA > acc) = 1 - \exp(-\upsilon\; t\; p(a)) \tag{3}$$

$$P(a) = P(PGA > acc \mid EQ) \tag{4}$$

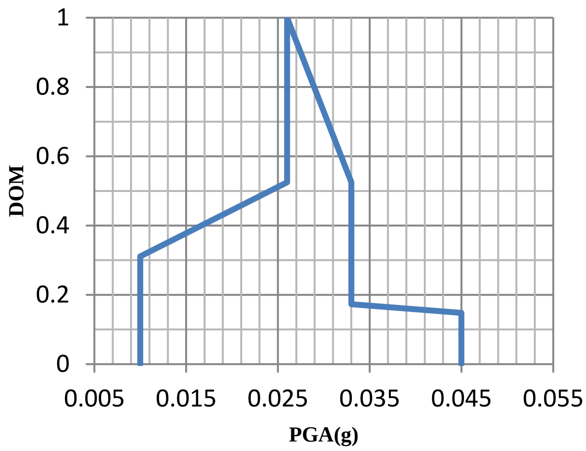

Fig. 4 PGA of various DOM for magnitude range of 4.5 to5 and distance range of 10 to 20 km

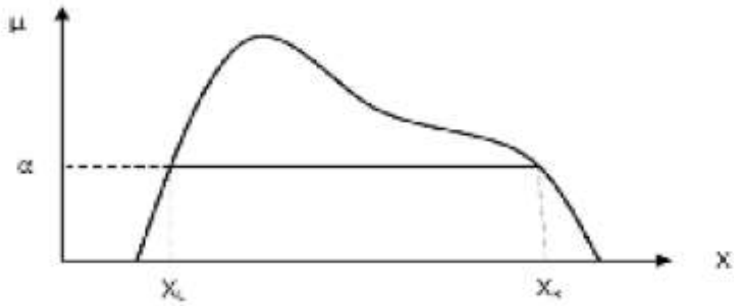

Fig. 5 α cut

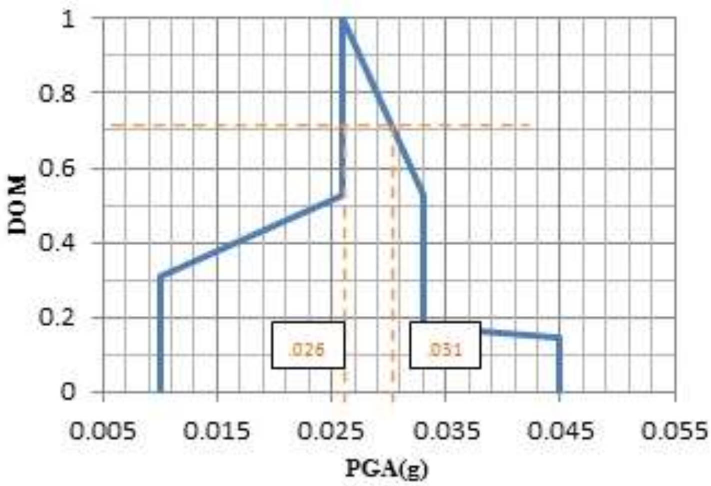

Fig. 6 PGA range for DOM of 0.7

Table 7 PGA range of every DOM for magnitude range of 4.5 to 5 and distance range of 10 to 20 km

DOM	PGA Range (g)	DOM	PGA Range (g)
1	0.026	0.4	.017 - .033
0.9	.026 - .028	0.3	.010 - .033
0.8	.026 - .029	0.2	.010 - .033
0.7	.026 - .031	0.1	.010 - .045
0.6	.026 - .032	0	.010 - .045
0.5	.025 - .033		

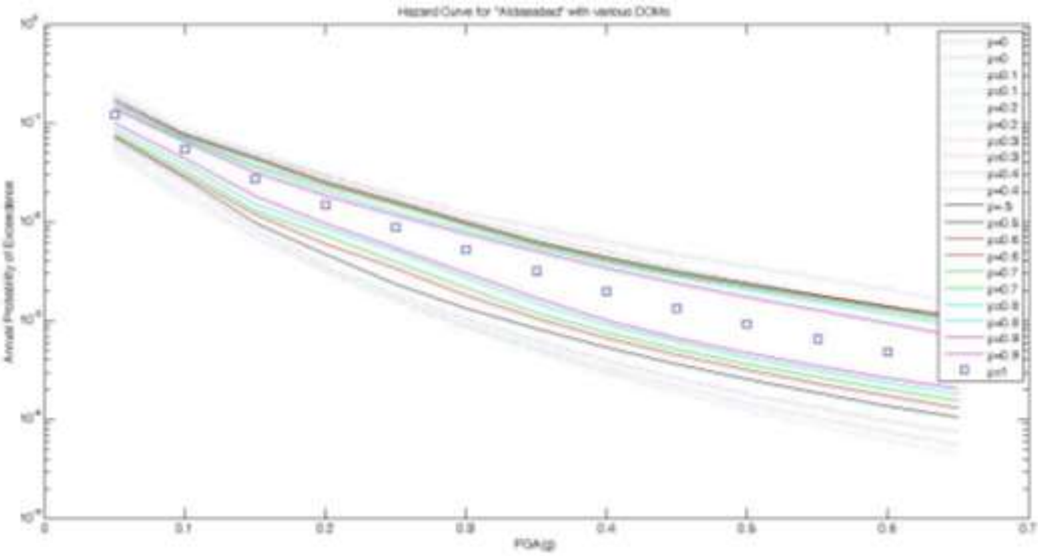

Fig. 7 The new method’s hazard curve for Abbasabad region with various DOMs

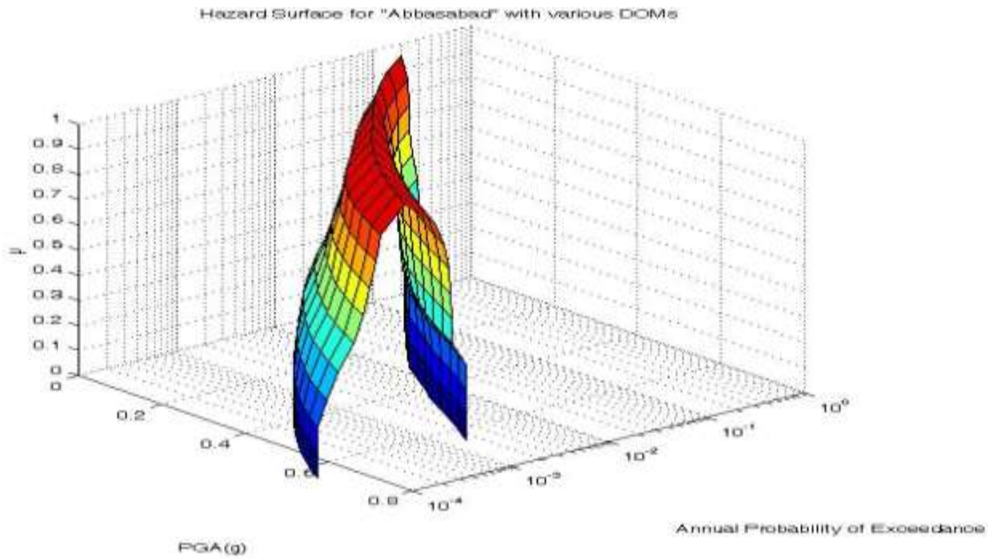

Fig. 8 The new method’s hazard surface for Abbasabad region

Table 8 Peak ground acceleration results using various DOMs for the return period of 475 years

Abbasabad	
DOM	PGA Range
1.0	0.390
0.9	0.335-0.470
0.8	0.325-0.490
0.7	0.300-0.500
0.6	0.290-0.510
0.5	0.255-0.525
0.4	0.245-0.530
0.3	0.238-0.600
0.2	0.235-0.600
0.1	0.235-0.600
0.0	0.235-0.600

Results for Abbasabad region shown in Figs. 7 and 8.

As can be seen, the PGAs for this region, assuming 10% chance of failure in the life expectancy of 50 years (return period of 475 years), shown in Table 8.

As can be seen in the figures and tables, final PGA results had the greatest DOM changes between μ=1 and 0.9 and gradually the PGA differences were reduced between the lower DOMs.

This means that the slightest inaccuracy in choosing appropriate GMPE would cause drastic changes in the final results. For example, in Abbasabad region, the PGA range in μ=0.9 was 0.335-0.47 g. (return period of 475 years). This wide range of PGAs showed the error ranges in selecting appropriate equations.

In logic tree method, using engineering judgment, the desired relationship with various normalized weight is elected. It is clear that the 90% confidence level for engineering judgment is considered as a good judgment. But here, because of major changes in the PGA results in bigger DOMs, the result for μ=1 can be only used. Therefore, the engineering judgment cannot be simply used and its PGA results cannot be trusted. As was illustrated before, the normalized weight in logic tree method is just assigned to the equations and there is no difference in the magnitudes and distances of those relationships. So, it is lucky to gain μ=0.9 for trust using this method; in such a case, there will be many errors in the PGAs of μ=0.9 than that of μ=1.

This method not only suggests the best result for final PGA, but also shows the PGA ranges, given the required level of risk.

In order to make a better comparison, the result of this new method was compared with the combination of GMPEs using logic tree method. For a reasonable logic tree it is desired to select the most weight for the Iran GMPEs. Because the most data in these relations are from Iran and has the most compatibility with Tehran site conditions and its characteristics. To consider the other conditions and factors and have a broader range of data lower weights are selected for Middle East and worldwide relations. Thus, Ghodrati’s relationship weight was 0.20, Nowroozi’s was 0.20, Zare’s was 0.20, and total weight of 0.6 was assigned to Iran’s relationships. Also, Ambraseys’ relationship weight was 0.15, Bommer’s was 0.15, and total weight of 0.30 was assigned to the Middle East. Finally, Sarma’s relationship weight was 0.05, Graizer’s was 0.05, and the total weight of 0.10 was assigned to the worldwide relationships (Table 9). The result of hazard curve for this logic tree compared to the results of the new fuzzy method for Abbasabad region shown in Fig. 9.

As can be seen in Fig. 8, the logic tree's hazard curve was between the hazard curve of μ=0.9 and 1 in the most of graph, showing that the logic weighing was appropriate and rational. But, the final PGA result was very different. The peak ground accelerations for this region, assuming the return period of 475 and 950 years using this logic tree, were 0.48 and 0.60 g, respectively. But, the PGA results using the new fuzzy method were 0.39 and 0.47 g (for μ=1).

The final hazard curve using the new method and the comparisons of the results of the new method with those of logic tree model for Shahrak-Laleh and Baghershahr shown in Figs. 10-15.

Table 9 GMPE weights in logic tree method

District	District Weight	Relationship Type	Relationship Weight
Iran	0.6	Ghodrati 2007	0.2
		Nowroozi 2005	0.2
		Zare 1999	0.2
Middle East	0.30	Ambraseys 2005	0.15
		Bommer 2003	0.15
Worldwide	0.10	Sarma 1996	0.05
		Graizer 2007	0.05

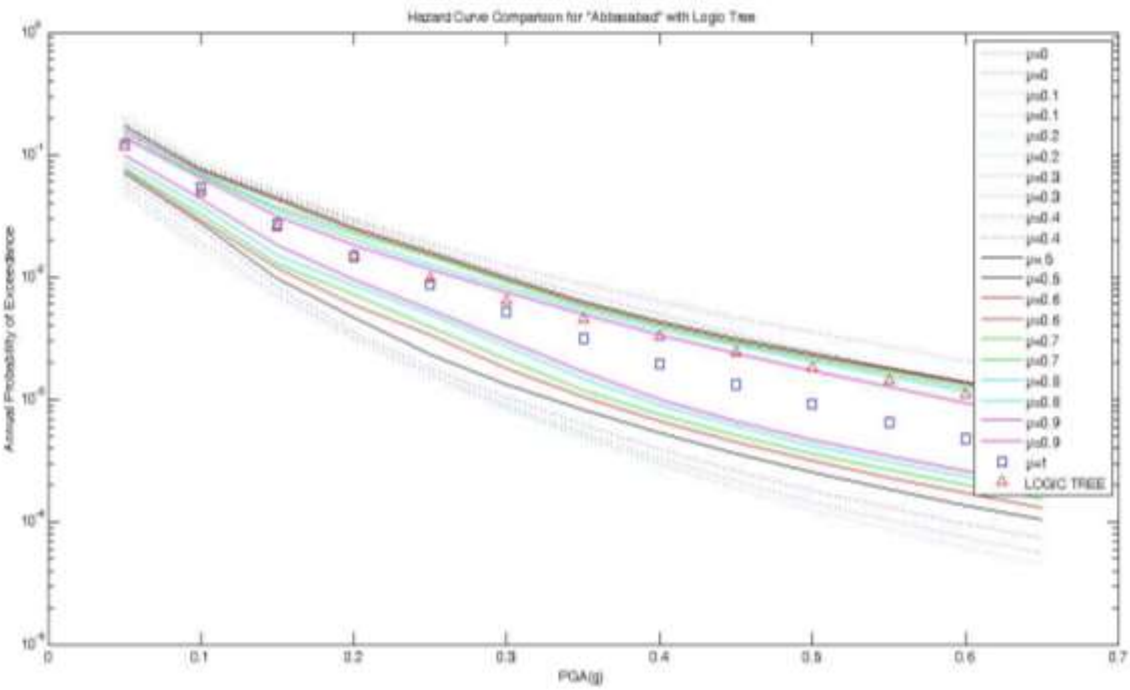

Fig. 9 Comparing the new method's hazard curve with the proposed logic tree hazard curve for Abbasabad region

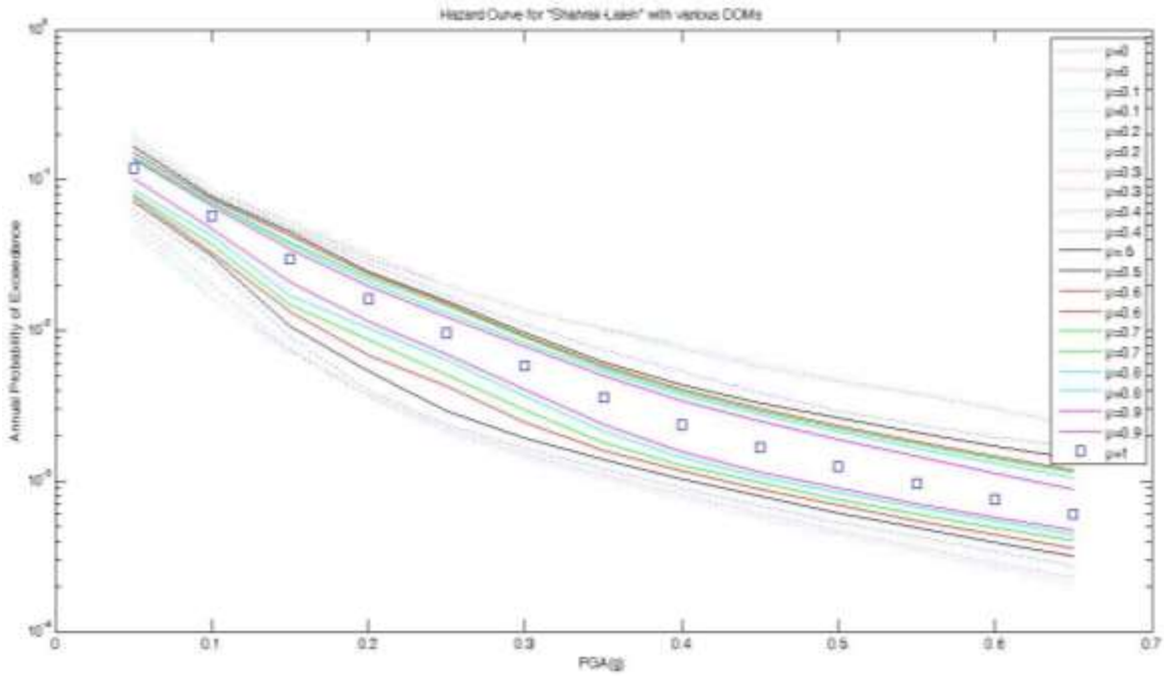

Fig. 10 The new method’s hazard curve for Shahark-Laleh region with various DOMs

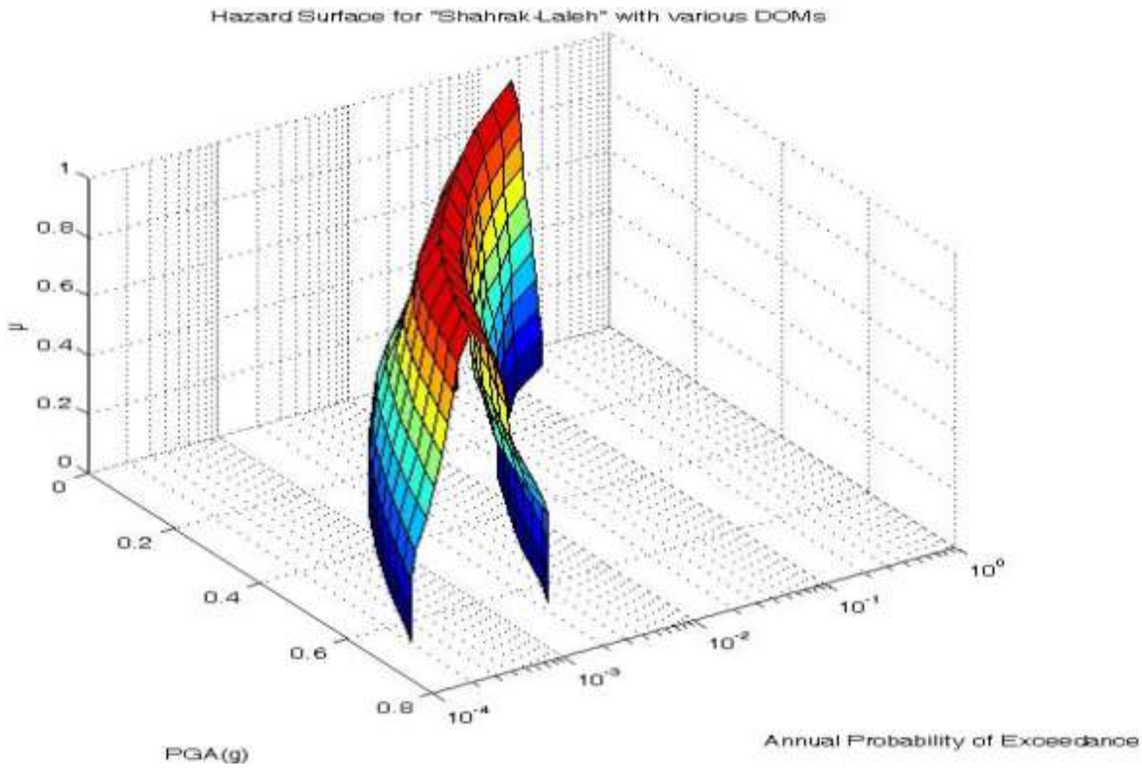

Fig. 11 The new method’s hazard surface for Shahrak-Laleh region

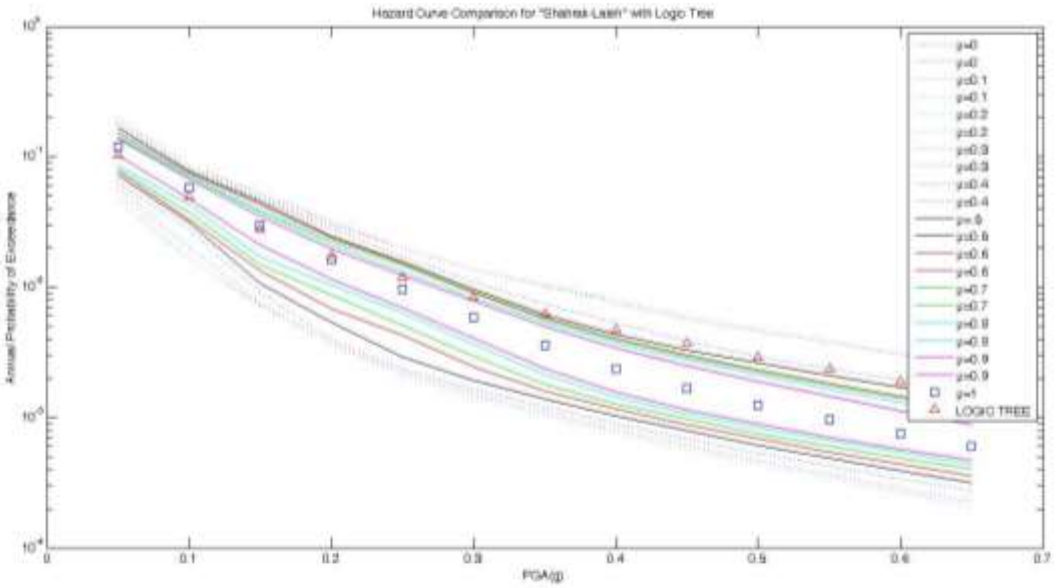

Fig. 12 Comparing new method’s hazard curve and the proposed logic tree’s hazard curve for Shahrak-Laleh region

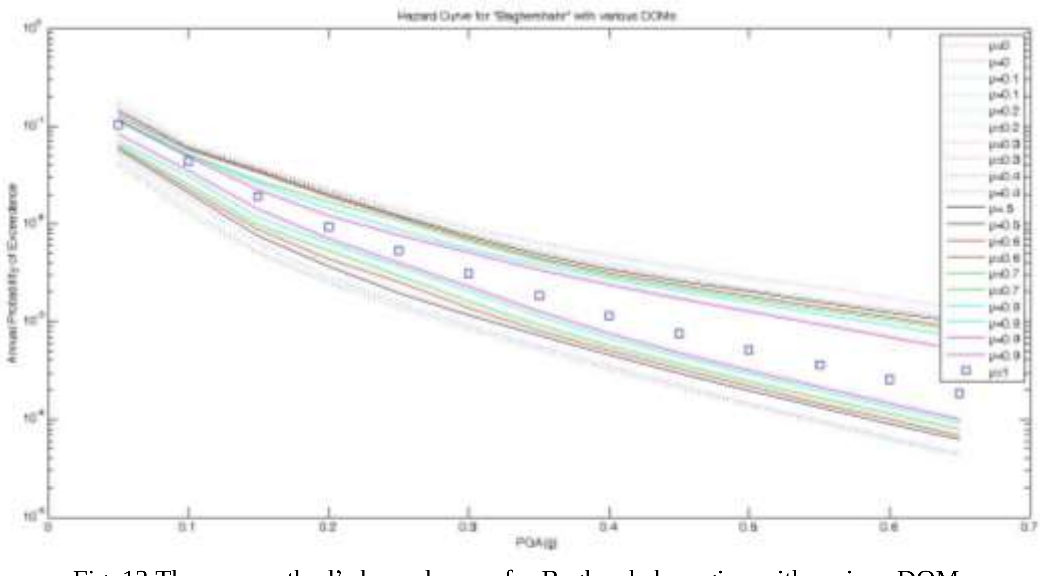

Fig. 13 The new method’s hazard curve for Baghershahr region with various DOMs

The results of these charts showed that most GMPEs acted conservatively in the magnitude and distance areas with a low number of input, which led to a larger amount of PGAs.

This issue could make significant difference to the final hazard curve and PGA. As can be seen in the figures, the PGAs of the new method, assuming return period of 475 years for Shahrak-laleh and Baghershahr, were 0.42 and 0.34 g, respectively. But, the PGA was 0.58 and 0.44 g, respectively, in the discussed logic tree method for those regions. So, there was more than 30%

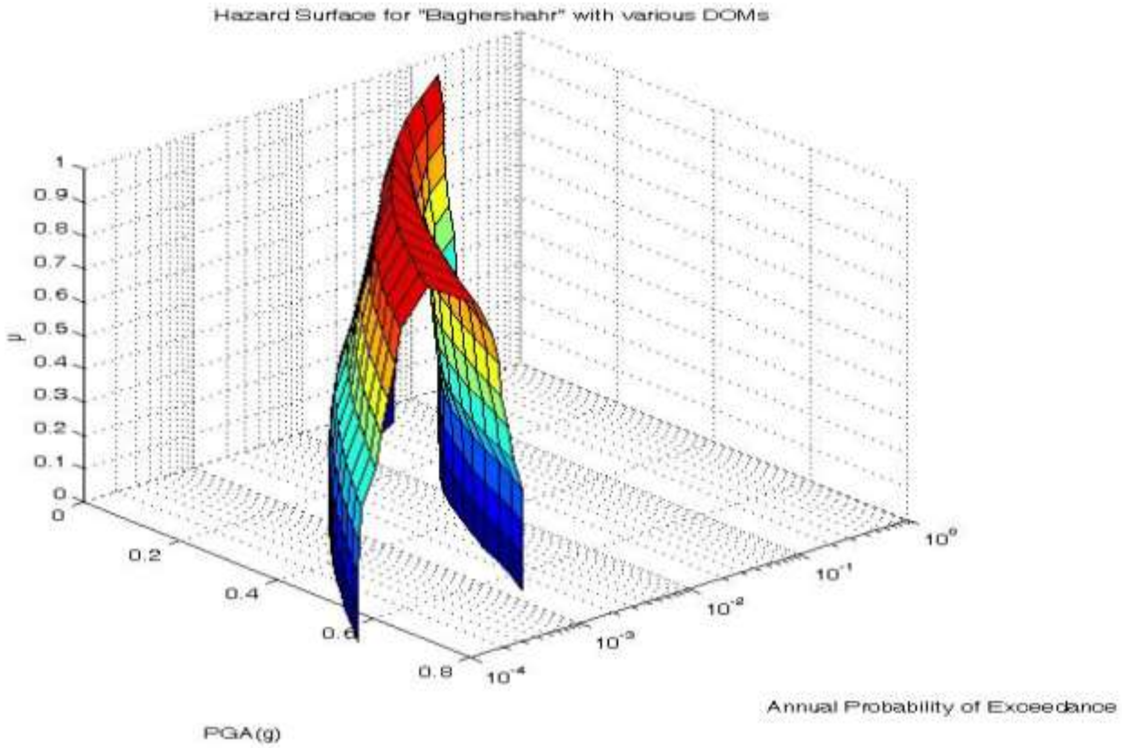

Fig. 14 The new method's hazard surface for Baghershahr region

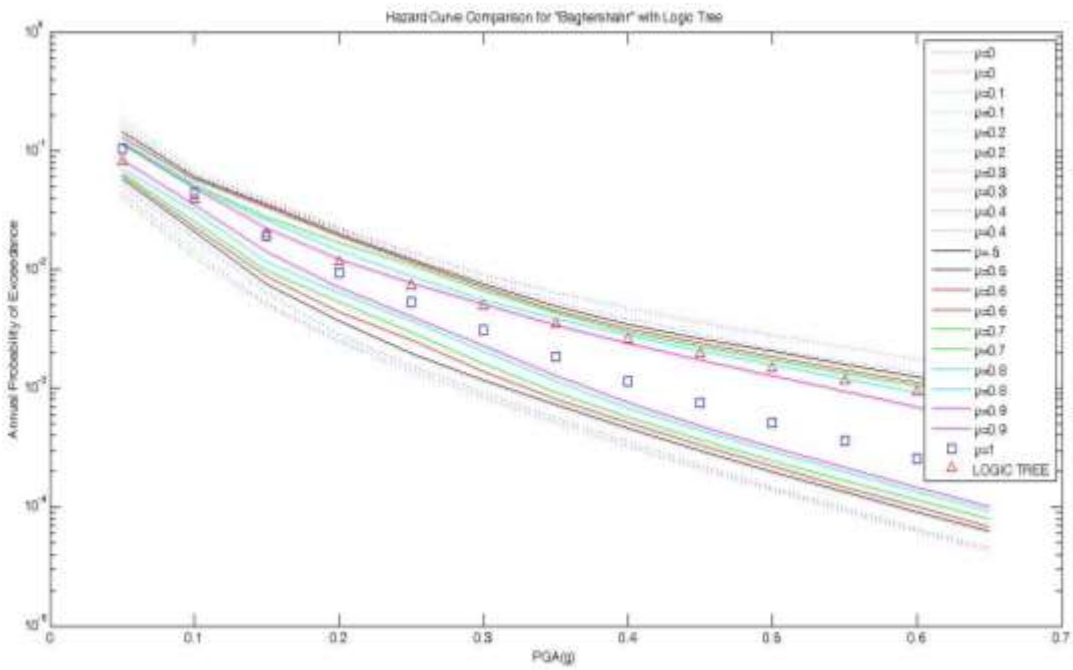

Fig. 15 Comparing the new method's hazard curve and the proposed logic tree's hazard curve for Baghershahr region

error in the PGA results in all the studied regions. Here is a simple comparison with Ghodrati's paper in 2003. The PGA results of the return period of 475 years and the same initial conditions for Abbasabad, Shahrak-Laleh, and Baghershahr regions on that paper were 0.39, 0.44, and 0.34 g, respectively. So, the new method's result had good compatibility with this result.

Therefore, the proposed method not only increased the accuracy of the final result, but also given the wide range of PGA variation because of equations and possible confusion and difference of opinion on engineering judgment, eliminated the possibility of divergent opinions.

Beside these advantages it should not be forgotten that the number of initial data points used in regression analysis is not the only concern in assigning the DOMs of different GMPEs and obtaining the final result but there are multiple physical factors like seismic source characteristics, wave propagation, path effects and etc. that affect the GMPE form and the final result.

4. Conclusions

In this paper, due to the importance of Ground Motion Prediction Equation(GMPE) in PSHA and the dramatic impact of this relationship on the results of the final PGA, a new method was proposed for selecting the appropriate GMPE at every intensity (earthquake magnitude) and distance (fault to site distance). Since most of the GMPEs using statistical regression techniques were obtained from the initial input database, the power and accuracy of the relationship were within the specific intensities and distances that had greater participation in the initial data. So, instead of using one equation in PSHA or dealing with several equations of different weights yet with the same effect on the magnitude and distance (logic tree), this powerful method could provide the best accuracy in selecting proper relationship at every magnitude and distance without engineering judgment. In other words, using this method, not only the relationship weight, but also the magnitude-distance weight would affect the relationship selection.

As observed by PSHA in three different locations in Tehran, using the logic tree method, no suitable weighting between the relationships could achieve the desired results in all the three areas. So, this method can easily and accurately result in the best answer by combining the chosen GMPEs at different magnitudes and distances.

Also, it was found that the major difference in the final PGA results occurred between μ=0.9 and 1. So, the appropriate relationship selection was not enough, because based on the best engineering judgment, it would come close to μ=0.9 and there would be a big difference in PGA of μ=0.9 and PGA of μ=1. So, the need for weighing at every magnitude and distance of every equation due to initial database seems to be necessary. Using the proposed fuzzy method and DOMs at every magnitude and distance of the chosen relationship, the referred gap will be filled.

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