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New Method of Choosing Ground Motion Prediction Equations in Probabilistic Seismic Hazard Analysis

[1]Mostafa Mahmoudi, [2]Mohsenali Shayanfar, [1]Mohammad Ali Barkhordari and [3]Ehsan Jahani
[1]Department of Civil Engineering, Iran University of Science and Technology, Tehran, Iran
[2]Centre of Excellence for Fundamental Studies in Structural Engineering,
Iran University of Science and Technology, Tehran, Iran
[3]Faculty of Engineering and Technology, University of Mazandaran, Babolsar, Iran

Abstract: Appropriate selection of Ground Motion Prediction Equation (GMPE) is one of the most important parts of Probabilistic Seismic Hazard Analysis (PSHA). This relationship is a mathematical equation which calculates the ground motion parameters as a function of earthquake magnitude, distance, site conditions and possibly other parameters using various regression methods. Each of these GMPEs uses the preliminary data of the selected earthquakes. In this study, considering the fundamental role of these equations in PSHA, an alternative method was proposed to select suitable equation at every intensity (earthquake magnitude) and distance (site distance to fault) according to the preliminary data aggregation at every intensity and distance. The results show that the use of this method makes a significant difference to the PSHA results over 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.

Key words: Motion parameters, earthquake, magnitude, site conditions, preliminary data

INTRODUCTION

Now a days, due to the irreparable disasters and events that have occurred as a result of earthquakes in the world and the incredible loss of life and property, there is not a slightest doubt about the importance of investigating the earthquake and the dangers thereof. It is an undeniable truth that with the current knowledge of human, earthquake-resistant design of structures and retrofitting the existing structures are the only ways for dealing with this natural disaster. Without a doubt, the first step is to analyze and evaluate the risks of earthquake and obtain a good estimate of earthquake forces. In other words, all these facts demonstrate the importance of the research for the analysis and evaluation of earthquake risks.

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

In such cases, the use of statistics and probability is the only option for analyzing these phenomena. By combining the concepts of seismic geotechnical studies with possibility, Probabilistic Seismic Hazard Analysis (PSHA) has emerged which is the most common, complete and the best method for seismic hazard assessment. The methodology of PSHA was first introduced by Cornell (1968) and has undergone prominent development since then. More investigations are described in detail in some publications such as Earthquake Engineering Research Institute in 1989.

Using this method, the uncertainty of various parameters can be considered and any changes in the location and magnitude of the earthquake can be properly affected. The purpose of PSHA is thereasonable 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 condition. An appropriate attenuation equation not only can help us 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 (Campbell, 1981; Kobielak *et al*., 2007; Cichowicz, 2010) as well as Iran (Nowroozi, 2005; Ghodrati Amiri *et al*., 2007). However, there are big

Corresponding Author: Mostafa Mahmoudi, Department of Civil Engineering, Iran University of Science and Technology, Tehran, Iran

differences in the results of equations which arise from various applied data sets (Abrahamson and Shedlock, 1997).

MATERIALS AND METHODS

These relationships are mathematical equations which calculate the ground motion parameters as a function of earthquake magnitude, distance, site conditions and possibly other parameters using various regression methods. Since, the ground motion parameters are used by engineers in the seismic design of structures the importance of these relationshipsiswell characterized. These relationships are based on statistical analysis of the recorded earthquake data. Given the importance of GMPE and dramatic impact on the final result of the earthquake risk analysis, selecting the appropriate equation in PSHA is the most important factor. Numerous works have been conducted in this field. The most common method for selecting or mixing the appropriate GMPEs 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 the appropriate equations. A logic tree in PSHA is described as follows: all the 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 isassigned to each branch.

The first step in logic tree method is to choose the appropriate equations for the studied area. Afterwards, a number between 0 and 1 has to be assigned to every relation which is called normalized weight number and reflects the analyst's confidence in the choice of the most correct relation. Choosing appropriate weight number is a challenging subject (Bommer, 2012). The hazard calculation is then performed following all the possible branches. However, this method has two major weaknesses. First, since assigning weight of each of the selected equations needs a specialist's opinion, many conflicts and errors can occur. Second, each of the selected equations in this method will have a similar impact on all the 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 the specialist's trust in that relationship is 30% and it is similar for all the intensities and distances. It is known that every equation 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 regression and creation of the relation. So, for obtaining accurate results it is necessary to avoid using one normalized weight for all the magnitudes and distances in one GMPE.

Table 1: Cumulative values for distances (fault to site distances) by Ambraseys *et al.* (2005)'s relation

Distance range (km)	No. of data	Normalized weight
0-10	81	0.60
10-20	136	1.00
20-30	94	0.69
30-40	80	0.59
40-50	57	0.42
50-60	37	0.27
60-70	36	0.26
70-80	38	0.28
80-90	15	0.11
90-100	19	0.14
100-110	0	0.00

The method presented in this study selected an appropriate GMPE for each earthquake intensity and fault to site distances based on the preliminary data aggregation at every intensity and distance. In fact, in this method, selecting one attenuation relation is not going to be trustworthy for every magnitude and distance but the appropriate equation will be chosen for each magnitude and distance.

Research direction: Since, most of GMPEs using statistical regression techniques areobtained 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 attenuation diagram 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. Therefore, in this new method for each intensity and distance an attenuation relation that hadthe most initial data in that area was selected.

Cumulative graphs for distances (fault to site distances) in GMPE: In this phase, cumulative values (normalized weight) for fault to site distances, according to the input database of each relation are separately calculated. Interval distance of 10 km is selected and given the number of input data in each of the intervals the aggregation number is assigned. Then, all values are divided by the maximum aggregation number to obtain the normalized weight for the distance. For example, Table 1 and Fig. 1 by Ambraseys *et al.* (2005)'s relation are shown.

As can be seen in the above chart, most data in the Ambrasey's relation range from 10-20 km, i.e., the highest level of reliability to this relation from the distance point of view is withinthis range. Also, it shows that at the distances of >110 km, this relation is slightly reliable.

Cumulative graphs for earthquake magnitude in GMPE: In this phase, cumulative values (normalized weight) for

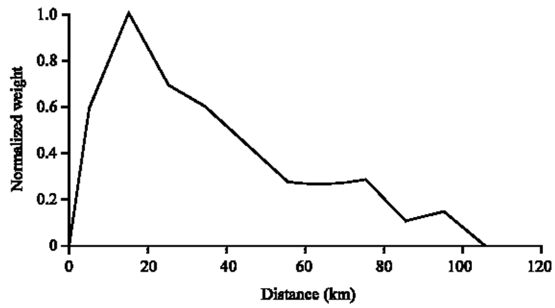

Fig. 1: Cumulative diagram for distances (fault to site distances) by Ambraseys *et al*. (2005)'s relation

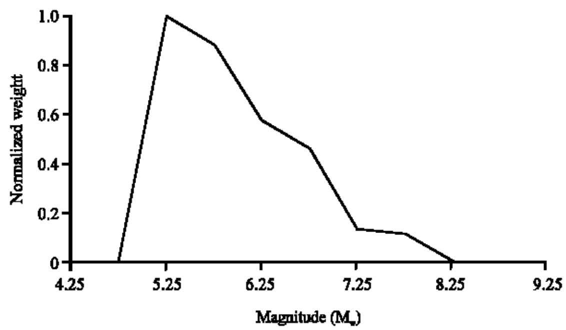

Fig. 2: Cumulative diagram for earthquake magnitude by Ambrasey *et al*. (2005)'s relation

earthquake magnitude, according to the input database of each relation are separately calculated. Interval magnitude of $\Delta m = 0.5$ is selected and given the number of input data in each of the intervals the aggregation number is assigned. Then, all values are divided by the maximum aggregation number to obtain the normalized weight for the earthquake intensity. For example, Table 2 and Fig. 2 by Ambraseys *et al*. (2005)'s are shown.

As can be seen in the above chart, most data in Ambraseys *et al*. (2005)'s relation range from magnitude of 5-5.5 the highest level of reliability to this relation from the magnitude point of view is within this range. Also, it shows that at the magnitude of >8.5 and <4.5 this relation is slightly reliable.

Combining magnitude and distance graphs: At this stage, given the normalized weight particularly gained by each of the equations the final normalized weight is obtained for the specific magnitude and distance for every relation. The reliability index of the magnitude and distance combination is the minimum normalized weight of magnitude and distance. For example, the magnitude normalized weight for Ambraseys *et al*. (2005)'s relation between the intensity range of 6 and 6.5 is 0.58 and the distance normalized weight for this relation between the distance range of 40 and 50 km is 0.42. So, the final

Table 2: Cumulative values for earthquake magnitude by Ambraseys *et al*. (2005)'s relation

Magnitude range (Mw)	No. of data	Normalized weight
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

normalized weight for this relationship in the magnitude range of 6-6.5 and distance range of 40-50 km is minimum of 0.58 and 0.42 as 0.42. For more details, the final normalized weights of Ambrasey's relation are presented Table 3.

The same calculation should have been done for all of the chosen GMPEs of the studied area. The numbers (normalized weight) in each cell represent the power and precision of the relationship at that intensity and distance. Then, the applicable equation for each cell, according to the maximum number of cells in all the chosen equations is selected for the studied site and PGA (Peak Ground Acceleration) is determined by the selected relationship at that distance and magnitude. Using this method, not only the relation weight but also the magnitude-distance weight will affect the relationship selection.

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 the fact of 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. Therefore, destruction of this city will have severe effects on the whole country. 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 7. Therefore, Tehran's seismic safety is extremely important and various investigations should be done in this regard. In this study, the probabilistic seismic hazard of Tehran was analyzed using the proposed method. Then, the results were compared with those of other relations and logic tree method. The three districts of Tehran with the following characteristics were selected for the analysis:

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

Table 3: Final normalized weights for every magnitude-distance by Ambraseys *et al.* (2005)'s relation

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	0.60	1.00	0.69	0.59	0.42	0.27	0.27	0.28	0.11	0.14
4-4.5	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.5-5	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5-5.5	1	0.60	1.00	0.69	0.59	0.42	0.27	0.27	0.28	0.11	0.14
5.5-6	0.88	0.60	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

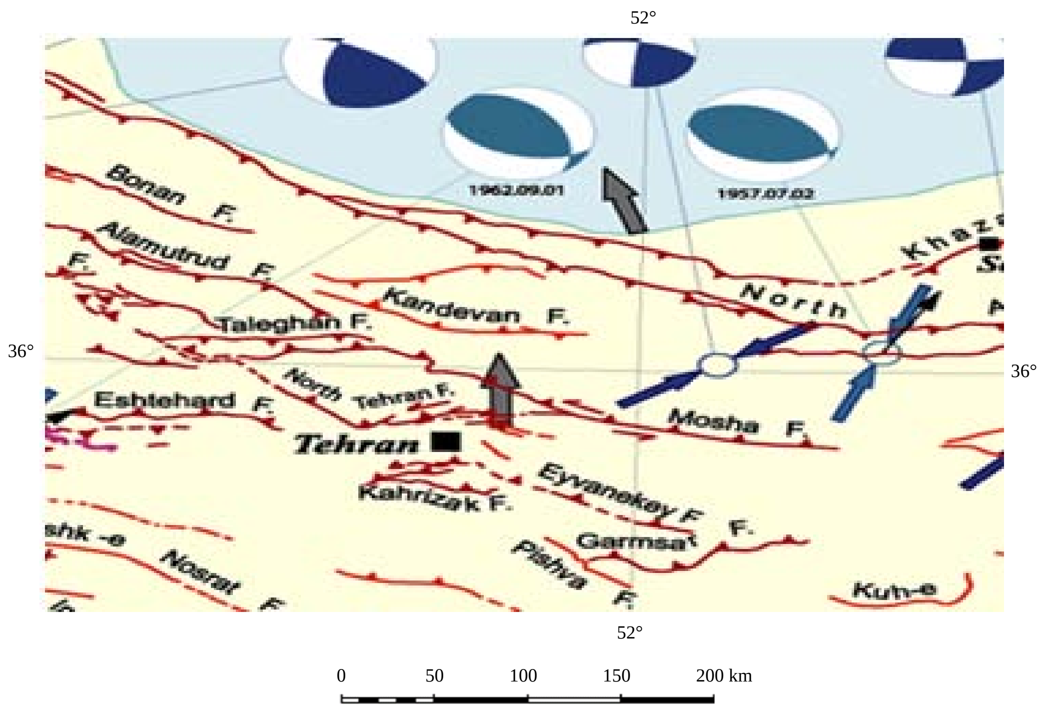

Fig. 3: The major faults surrounding Tehran

Site: soil, 175 m/sec<V_s<300 m/sec
$m_0 = 4$
$\lambda(4) = 0.37$, $\beta = 1.41$ (Tavakkoli)
$\lambda(4) = 0.63$, $\beta = 1.08$ (Ghodrati)
Style of faulting: Reverse

It should be noted that the used rate of earthquake activity (λ) was obtained by assigning the same weightvalue 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 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 (Fig. 3). The most important faults that can be detected in the range of target zone were the following 8 faults (Table 4).

Table 4: Characteristics of major faults in Tehran

Faults	Length (km)	M_{max}
Mosha	200	7.5
N.Tehran	75	6.9
Niavaran	13	6.0
N-Ray	17	6.1
S-Ray	18.5	6.2
Kahrizak	40	6.6
Garmsar	70	6.9
Pishva	34	6.5

RESULTS AND DISCUSSION

Selecting GMPEs for probabilistic seismic hazard analysis of Tehran: In this study, based on Pacific Earthquake Engineering Research Center Report in 2011, seven equations were selected for Iran, among which 3 were related to Iran, 2 to the Middle East and 2 were worldwide. The relationships are described:

Table 5: Applicable GMPE for every magnitude-distance criterion for Tehran (Gh: Ghodrati's relationship, Bo: Bommer's relationship, Am: Ambrasey's relationship, No: Nowroozi's relationship, Za: Zare's relationship, Gr: Graizer's relationship, Sar: Sarma's relationship)

Distance (km)/ Magnitude (Mw, Ms)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120
3.5-4	Bo.	Za.	Za.	Za.	Bo.	Bo.	Bo.	Gr.	Gr.	Gr.	Gr.	Gr.
4-4.5	Bo.	Bo.	Za.	Gh.	Gh.	Gh.	Gh.	Gh.	Gh.	Gr.	Gh.	Gr.
4.5-5	Bo.	Za.	Gh.	Gh.	Gh.	Gh.	Gh.	Gh.	Gr.	Gr.	Gr.	Gr.
5-5.5	Bo.	Am.	Am.	Gh.	Gh.	Gh.	Gh.	Gr.	Gr.	Gr.	Gr.	Gr.
5.5-6	Bo.	Am.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.
6-6.5	Am.	No.	Gr.	Gh.	Gr.	Gr.	Gh.	Gr.	Gr.	Gr.	Gr.	Gr.
6.5-7	Sa.	No.	No.	Sa.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.
7-7.5	Sa.	No.	No.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.
7.5-8	No.	No.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.	Gr.
8-8.5	No.	No.	No.	No.	No.	No.	No.	No.	No.	No.	Gr.	Gr.

Table 6: Peak ground acceleration results usingvarious relations for the return period of 475 years

GMPE type	PGA
Return period of 475 years	
New method	0.39
Ghodrati	0.43
Zare	0.47
Nowroozi	0.50
Ambraseys	0.55
Bommer	0.37
Sarma	0.33
Graizer	0.65

- Ghodrati Amiri *et al.* (2007)
- Zare
- Nowroozi (2005, 1976)
- Ambraseys *et al.* (2005)
- Bommer (2012)
- Sarma and Srbulov (1996)
- Graizer and Kalkan (2007)

For this example, the range of earthquake magnitude was between 4 and 8 with the magnitude interval of $\Delta m = 0.5$ 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 10 rows and 12 columns was formed and the value entered for each cell was the final normalized weight for the specific magnitude and distance by the specific relationship. Then, the applicable relationship for each cell, according to the maximum number of cells in all 7 chosen equations was selected. Table 5 shows the applicable GMPE for every magnitude and distance for Tehran. Then, according to the governing relation and basic information analysis was done. The result of Abbasabad region is shown as followed. As can be seen assuming 10% chance of failure in the life expectancy of 50 years (return period of 475 years), the PGA for this region was 0.39 g. Then, the same analysis was performed for this region using the 7 equations separately and the results are exhibited together (Fig. 4 and 5). Assuming 10% chance of failure in the life expectancy of 50 years using each relationship, peak ground acceleration for this region is shown as follows in Table 6.

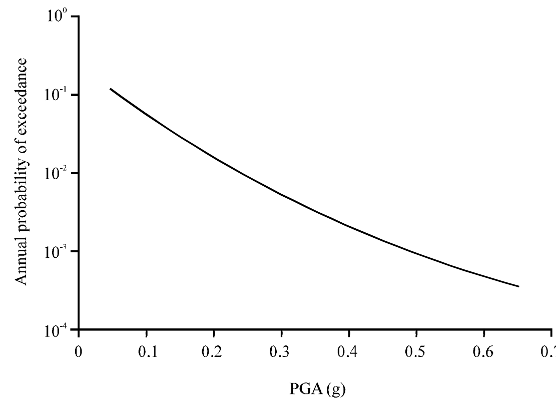

Fig. 4: Hazard curve of the new method for Abbasabad region

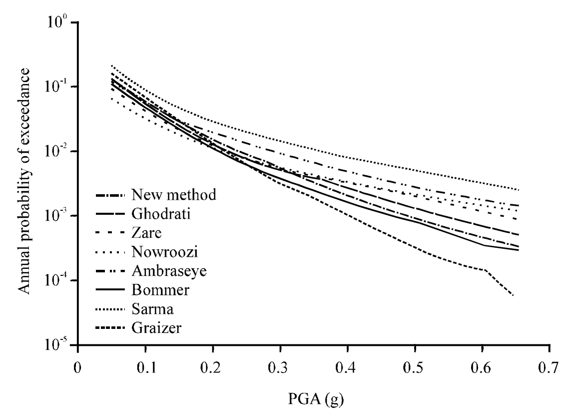

Fig. 5: Comparing the new method's hazard curve with that of individual GMPE for Abbasabad region

In order to make a better comparison, the result of this new method was compared with the combination of GMPEs using logic tree method. 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, Ambrasey's 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

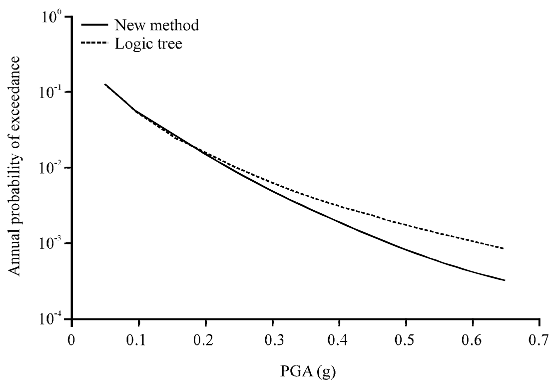

Fig. 6: Comparison of the new method's hazard curve with the proposed logic's tree hazard curve for Abbasabad region

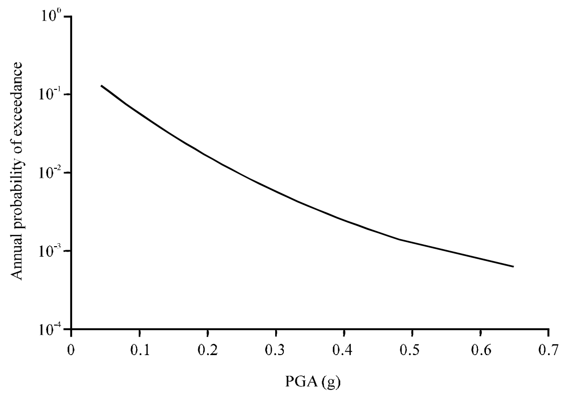

Fig. 7: The new method hazard curve for "Shahrak-Laleh" region

weight was 0.05, Graizer's was 0.05 and the total weight of 0.10 was assigned to the worldwide relationships (Fig. 6).

The result of hazard curve of this logic tree compared to the results of the new method for Abbasabad region is shown in Table 7. Comparisons of the new method with individual relation and logic tree model for Shahrak-Laleh and Baghershahr are shown in Fig. 6-12. 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 charts, the PGAs of the new method assuming 10% chance of failure in the life expectancy of 50 years for Abbasabad, Shahrak-Laleh and Baghershahr were 0.39, 0.34 and 0.44g, respectively. But, the range of the PGA in the discussed relations for those regions was 0.34-0.55, 0.34-0.55 and 0.34-0.55 g, respectively. Here is a simple comparison with Ghodrati's study in 2003. The result of PGAs of the same

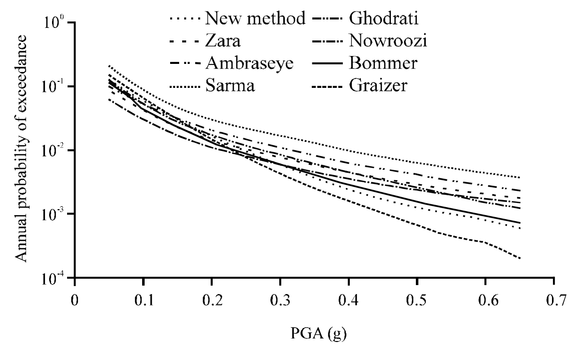

Fig. 8: Comparison of the new method's hazard curve with that of individual GMPE for Shahrak-Laleh region

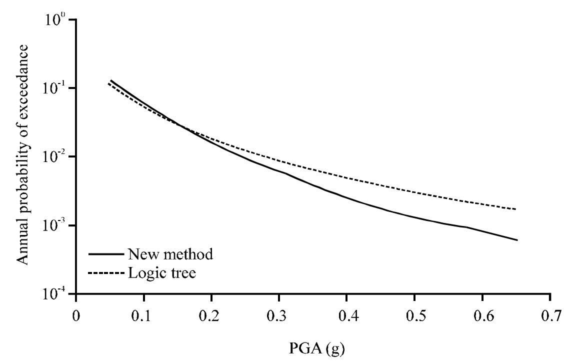

Fig. 9: Comparison of new method's hazard curve with that of the proposed logic tree for Shahrak-Laleh region

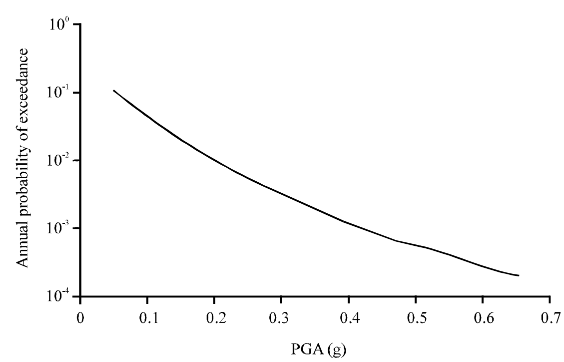

Fig. 10: The new method's hazard curve for Baghershahr region

return period and initial conditions for those regions in that study were 0.39, 0.33 and 0.45 g, respectively (Fig. 8-12).

Therefore, the proposed method not only increased the accuracy of the final result but also given the wide range of PGA variation because of various GMPEs and

Table 7: GMPEs weights in logic tree method

Districts	District weight	Relationship type	Relationship weight
Iran	0.60	Ghodrati Amiri *et al.* (2007)	0.20
		Nowroozi (1976)	0.20
		Zare	0.20
Middle East	0.30	Ambraseys *et al.* (2005)	0.15
		Bommer (2012)	0.15
Worldwide	0.10	Sarma	0.05
		Graizer and Kalkan (2007)	0.05

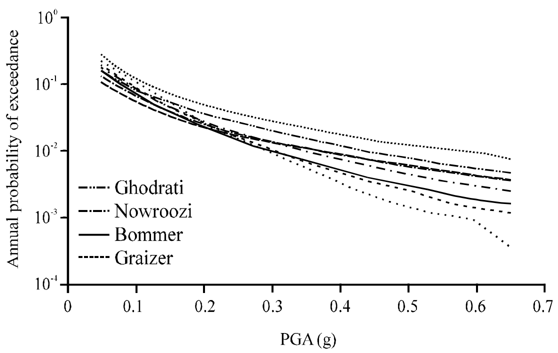

Fig. 11: Comparison of the new method's hazard curve with that of individual GMPE for Baghershahr region

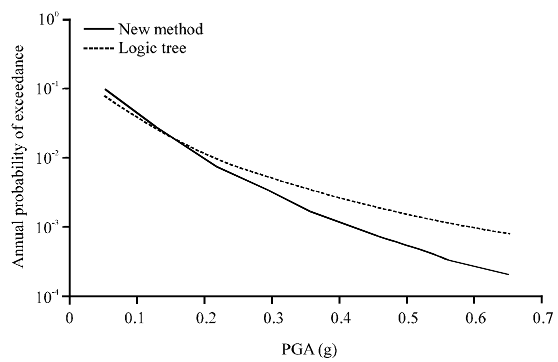

Fig. 12: Comparison of the new method's hazard curve with that of the proposed logic tree for Baghershahr region

possible confusion and difference of opinion on engineering judgment, eliminated the possibility of divergent opinions.

CONCLUSION

In this study, 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, by using this method not only would the relationship weight effect the relationship selection but also the magnitude-distance weight.

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 relations at different magnitudes and distances.

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