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Peak ground acceleration prediction by fuzzy logic modeling for Iranian plateau

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Abstract
In this study, fuzzy logic modeling is applied to a complex and nonlinear set of data to predict both horizontal and vertical peak ground accelerations in Iranian plateau. The data used for the model include an up-to-date seismic catalogue from earthquakes in Iran for prediction of both horizontal and vertical acceleration of a probable earthquake. Fuzzy logic toolbox on MATLAB program was used for modeling. Earthquake magnitude ranging from 4 to 7.4, source-to-site distance from 7 to 80 km and three different site conditions were considered: rock, stiff soil and soft soil. Results are compared with those from worldwide and regional attenuation relationships, which show the higher capability of the model in comparison with the other models. After training the model, testing of the fuzzy model with the remaining data set was performed to confirm the accuracy of the model. Changes in the peak ground accelerations in connection with changes in input parameters are studied which are in agreement with basic characteristics of earthquake input motions.

Keywords Attenuation relationships · Fuzzy logic modeling · Earthquake input motion · Peak ground acceleration

Introduction

Earthquake input motions are of paramount importance in engineering seismology. Attenuation relationships developed from records of ground motions usually used to estimate these input motions. In these relations, some independent factors such as magnitude, distance from source of the earthquake to site, faulting mechanism and site conditions are related to other dependent parameters such as peak ground acceleration through regression analysis. There are many factors that have been neglected on suggested equation for estimating ground motions such as subsurface topography variations, dynamic and static stress drop in the crust, radiation pattern and different decay rate for different types of waves (Anderson 1991; Boore 1983; Douglas 2001; Joyner 1987; Joyner and Boore 1988). Lack of information on these factors in the equations causes a large deviation in the developed relationships, which makes engineers use a large safety factors at their designs (Douglas 2002) or in some cases, use high input motion.

Ground motion prediction equations (GMPE) are improving every day. New earthquake data following with modern data analysis help researchers to review GMPEs and improve their reliability (Abrahamson et al. 2014; Boore et al. 2014; Campbell and Bozorgnia 2014; Chiou and Youngs 2014; Idriss 2014). Different attenuation relationships have been suggested for prediction of ground motion characteristics for worldwide, a country or a special zone (Ozmen and Babsbug Erkan 2014; Shoushtari et al. 2016). Attenuation relationships developed by Ambraseys and Douglas (2000), Bozorgnia et al. (2000), Campbell and Bozorgnia (2000) and Campbell and Bozorgnia (2003) are some examples for worldwide use, and those developed by Ambraseys et al. (1996), Ambraseys and Simpson (1996) and Bommer et al. (1998) are examples for Europe and Middle east. In connection with this study, attenuation relationships developed by Khademi (2002), Zare and Sabzali (2006) and Amiri et al. (2007) are those developed to predict ground motions in Iranian plateau.

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In the common methods of developing attenuation relationships, first recorded acceleration histories are analyzed and short- and long-period noises are removed from data. At the next step, useful dependent variable such as spectral acceleration or peak ground acceleration is derived from filtered acceleration histories, while independent variables such as source-to-site distance or magnitude are collected. At last complex analyses with the aim of best regression are performed to get an acceptable result for dependent variables (Douglas 2002). Some researchers have used magnitude, source-to-site distance and soil conditions in their relations (Ambraseys and Douglas 2000), and some others applied additional terms like source mechanism (Campbell and Bozorgnia 2000; Atkinson and Boore 2003; Bozorgnia and Campbell 2004). A comprehensive worldwide summary of strong-motion attenuation relationships was prepared by Douglas (2004). The next generation of attenuation relationships for shallow crustal earthquakes was developed in Pacific Earthquake Engineering Research Center (PEER) considering different site conditions (Abrahamson and Silva 2008; Boore and Atkinson 2008; Campbell and Bozorgnia 2008; Chiou and Youngs 2008; Idriss 2008). At recent years NGA WEST program (Next Generation of Ground-Motion Attenuation Models for the Western United States) and its enhancement NGA WEST 2 were developed at PEER in partnership with U.S. Geological Survey and southern California Earthquake Center to develop new ground motion relations (Boore et al. 2014; Campbell and Bozorgnia 2014; Idriss 2014).

Over the last 20 years, new variables have been added to ground motion prediction equation and made them more complex (Laurie et al. 2011). The majority of these models are empirical and with a large number of parameters and dependencies. Another drawback of these models is that they are developed based on a predicted linear or nonlinear equation, with the hypothesis of normality of residuals for testing the developed model (Thomas et al. 2016). The attenuation relationships suggested to be used world widely were developed based on data from different earthquake events on Earth, especially from those with high earthquake magnitude in different local areas. So, specific characteristics of data in local areas were not considered. On the other hand, the numbers of data in local areas are very low and their deviations and discrepancies are very high, which results in high standard deviations in the local attenuation relationships. Therefore, attenuation relationships are highly uncertain due to computational uncertainties and uncertainties of the input parameters. In this case, fuzzy logic method has several benefits as it uses the natural trends of the inspection data and applies flexible interference rules (Sun et al. 2002). Another advantage of fuzzy model is that it can be easily improved and updated by new data of new earthquakes, while this flexibility on both modeling process and updating data does not exist in the regression methods. In fuzzy logic modeling, nonlinear functions of arbitrary complexity can also be modeled and there is no need to insist on a predefined equation.

For the application of fuzzy logic theory in dealing with the earthquake input motions, some research studies were conducted on the signal processing and classification of acceleration time histories; classification of earthquake strong ground motion records was performed by Alimoradi et al. (2005) using fuzzy pattern recognition. They showed that Fuzzy logic approach was a promising analytical tool in the classification of design ground motion records. An algorithm based on fuzzy logic techniques was introduced by Tsiftzis et al. (2006) for the classification of signals of acceleration time histories according to the damage that they cause in buildings. Mierlus-Mazilu and Majercsik (2010) used fuzzy classification method for classification of signals of ground acceleration time histories to define seismic damage potential of ground motions. Jorjiashvili et al. (2012) discovered the role of the uncertainty of the data in the seismic hazard analysis through Fuzzy set theory; they found that when there are insufficient data for hazard assessment, site classification based on fuzzy set theory shows values of standard deviations less than those obtained using the classical way.

The only study on attenuation relationship via Fuzzy logic approach was conducted by Ahumada et al. (2015) for peak ground acceleration on different site conditions, which was based on selected data from PEER database. They showed that the epicentral distance and soil type have major effects on the attenuation characteristics; in comparison with other selected empirical attenuation relationships, their model had higher efficiency; however, they predicted only peak ground horizontal acceleration (PGHA) from data of 15 different earthquake events on Earth. A neuro-fuzzy approach was also proposed by Thomas et al. (2016) for predicting the peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD) using the database released by PEER; they compared their results with two other hybrid models of artificial neural network and genetic programming and showed that their method had comparatively higher accuracy and lesser computation time. They compared their results with prediction values from three attenuation relationships, but they did not discuss the trends of the output in connection with the input parameters; therefore, they did not investigate whether their method captured principles of earthquake ground motion or not.

The objective of this study is to predict both peak ground horizontal acceleration (PGHA) and peak ground vertical acceleration (PGVA) using fuzzy logic approach to deal with the uncertainties. The data from 28 different earthquakes in Iranian plateau are used with the independent input parameters including records of earthquakes with moment magnitude between 4.0 and 7.4, different site conditions of soft soil, soil and rock, and source-to-site distance from 7 to 80 km. These are three input parameters of the fuzzy model, and PGHA and PGVA are its output. After evaluation of the fuzzy logic model based on training and testing data, the results are compared with those from attenuation relationships developed by other researchers for worldwide and local area. The comparison shows improved performance and better efficiency of the developed fuzzy model. In addition, trends of both PGHA and PGVA in connection with input motion parameters are discussed which show that the developed fuzzy model exhibits the important characteristics of the earthquake input motion.

Fuzzy logic theory

In order to handle problems with imprecise data and ambiguity, the fuzzy logic technique was introduced and pioneered by (Zadeh 1965). The method is about the relative importance of precision (MATLAB 2000). It comes from fuzzy set theory dealing with reasoning that is approximate rather than just conclude from classical predicate logic. Fuzzy logic is a mathematical and an organized method of handling inherent inexact concepts and can be used as a new method or way for expressing probability. It can apply to different kinds of uncertainty. Probability works with chances of that happening but fuzzy logic deals with imprecision. This technique can be applied to a nonlinear and complex set of data. There are five different steps that process fuzzy interface:

- Fuzzification of input data; the first step is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. In this study, these membership functions are defined for magnitudes and source-to-site distance and site conditions.
- Application of the fuzzy operator; based on expert judgment, some logical rules are defined to correlate outputs to the inputs.
- Implication from the antecedent to the consequent; in this step proper weighting is assigned to each rule and implication method is applied, resulted in a fuzzy set represented by a membership function.
- Aggregation of the consequents across the rules; the rules are combined in order to make a decision, which is a single fuzzy set for the output.
- Defuzzification; here some methods are used to build a single number from the resultant fuzzy set (MATLAB 2000)

Each input parameter has a degree on membership functions in a fuzzy set. Higher probability of an input has a higher degree of membership. If a degree of an element is zero, it shows that the element is not a member of fuzzy set. For the case of this study, initial Gaussian membership functions for earthquake magnitude, source-to-site distance and site conditions are shown in Fig. 1. These inputs are ambiguous and imprecise and are the common input parameters of attenuation relationships. Because of the nature of fuzzy logic theory and its intrinsic feature in dealing with uncertainty, fuzzy logic modeling is used in this study as a technique to predict both PGHA and PGVA of a probable earthquake.

Strong-motion database

The ground motion at a site depends on the source-to-site distance, energy released by the earthquake, local geologic conditions and rupture mechanism (Wadia-fascetti and Gunes 2000). For the definition of source-to-site distance, Joyner and Boore (1981) found that the correct distance for estimating ground motion parameters is the distance between the site and exact point of earthquake occurrence (hypocentral distance). Determination of this distance in the past earthquakes and its prediction for future earthquakes is very difficult. Therefore, the distance used at this modeling is epicentral distance that is the distance from the site to epicenter of an earthquake.

For the energy of an earthquake, moment magnitude (M_w) is used as another input parameter, which was used in many equations (Boore et al. 1993; Kobayashi et al. 2000; Lawson and Krawinkler 1994; Sadigh et al. 1997). For the local geologic or site conditions, shear-wave velocity in the top 30 m (Vs_{30}) of the site was considered as the input for the site condition, which was used in the recent developed attenuation relationships (Abrahamson and Silva 2008; Boore and Atkinson 2008; Campbell and Bozorgnia 2008; Chiou and Youngs 2008). Depending on the information of the site condition, categories such as "very soft soil," "soft soil," "stiff soil" and "rock" sites can be considered in the attenuation relationships. For instance, researchers such as Khademi (2002) and Amiri et al. (2007) used only general soil and rock conditions. However, in this study to be consistent with other attenuations relationships such as Boore et al. (1997), Ambraseys et al. (2005a, b) and Zare and Sabzali (2006), three different site conditions of rock, stiff soil and soft soil were considered with the definition described in Table 1.

Due to the lack of information in the recorded earthquake data, parameters such as rupture mechanism, hanging wall effect and alluvium depth were not considered in the developed fuzzy model. This keeps the model simple and consistent with other comparable attenuation relationships such as those developed by Boore et al. (1997), Khademi (2002), Zare and Sabzali (2006) and Amiri et al. (2007).

At this study, 316 acceleration records from 28 earthquake events in Iranian plateau were accessed from Road,

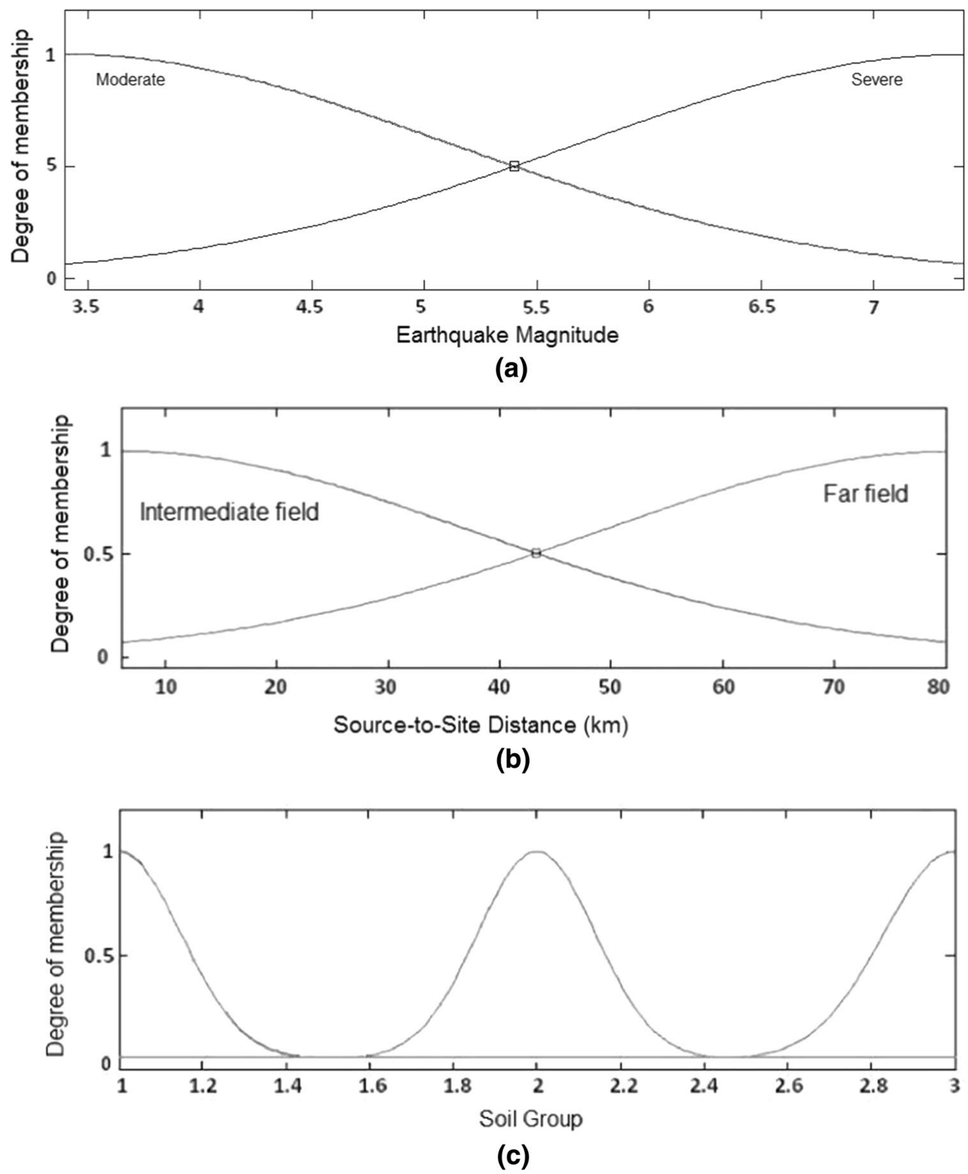

Fig. 1 Initial membership functions for **a** magnitude of earthquake, **b** source-to-site distance and **c** site condition

Table 1 Definition of the site condition in this study

Soil group	Site condition	$V_{s(30)}$ (m/s)
1	Rock	> 750
2	Stiff soil	350–750
3	Soft soil	< 350

Housing and Urban Development Center (2012). These data were collected from seismographs stations across the area. Each of the data involves the information of coordination of the station, date and time of earthquake, epicenter and magnitude of earthquake and acceleration record at two horizontal and one vertical direction. For the input of the model, source-to-site distance between 7 and 80 km and earthquake magnitude from 4 to 7.4 Richter were chosen.

For the output of the model, both horizontal and vertical accelerations were used. For the case of horizontal acceleration, average of two components of horizontal accelerations was used, which were in the range of 0.01–0.67 g. Because of the large number of data used for the modeling, some of these data are shown in Table 2 for examples. This includes data in the ranges that has been used in this study.

Modeling and fuzzy logic rules

Fuzzy logic toolbox in MATLAB program was used for fuzzy modeling (MATLAB 2000), in which moment magnitude, source-to-site distance and soil conditions were chosen as input parameters, and PGHA and PGVA were outputs. At first, three overlapped membership functions were used

Table 2 Example of data used for modeling

Nos.	Record	Station	Date	M_w	R (km)	Site	PGHA(1) m/s^2	PGHA(2) m/s^2	PGVA m/s^2
1	1012	Kiasar	11/05/1974	4.5	64	2	0.390	0.300	0.157
2	1006-1	Bandarabbas	03/07/1975	6.1	48	2	0.863	1.287	0.417
3	1006-2	Bandarabbas	03/07/1975	5.2	40	2	0.167	0.260	0.125
4	1007	Minab	03/07/1975	6.1	80	1	0.217	0.168	0.094
5	1008	Gheshm Island	03/07/1975	6.1	56	1	0.148	0.121	0.137
6	1013	Tonkabon	03/13/1975	4.4	34	3	0.428	0.192	0.102
7	1009	Minab	04/12/1975	4.8	48	1	0.357	0.154	0.077
8	1026	Shiraz	06/02/1975	4.1	60	3	0.505	0.251	0.286
9	1014-4	Hajiabad	10/08/1975	5.4	32	3	0.669	0.796	0.471
10	1024	Maraveh-Tappeh	12/27/1975	4.6	6	3	3.270	3.595	1.533
11	1034-1	Maku	02/27/1976	3.9	26	2	0.432	0.537	0.316
12	1034-2	Maku	04/02/1976	4.6	12	2	1.997	1.022	0.845
13	1040-3	Naghan-1	09/05/1976	4.7	88	1	0.437	0.495	0.452
14	1043	Ghaen	11/07/1976	6.4	10	1	1.150	1.570	1.700
15	1047-8	Vendik	11/07/1976	6.4	11	2	5.117	4.982	1.167
16	1047-9	Vendik	11/07/1976	4.8	9	2	1.750	1.559	0.674

for magnitude and source-to-site distance, but none of the simulation was good enough, so with the process of trial and error on the number of membership functions, better simulation was conducted with two-overlapped membership function for both magnitude and source-to-site distance. Membership functions for magnitude of earthquake (M) are called moderate and severe and for epicentral distance (D) are intermediate field and far field.

Soil condition (S) was classified into three different groups without any effect on each other, and because of this reason, there is no overlap of the membership functions. Figure 1 shows initial Gaussian membership functions for the magnitude of earthquake, source-to-site distance and site condition, respectively. It should be mentioned that due to the lack of data with epicentral distance less than 7 km, no membership function was considered for the near field earthquakes. In fact, the fuzzy logic model is proposed for the estimation of earthquake acceleration with the source-to-site distance between 7 and 80 km. This distance contains intermediate and far field distances.

Fuzzy rules for a sample data are defined as follows:

$$R: \text{ IF } M \text{ is } X_1 \text{ and } D \text{ is } X_2 \text{ and } S \text{ is } X_3$$
$$\text{then PGHA is } Y_1 \text{ and PGVA is } Y_2$$

X_1, X_2 and X_3 represent membership functions for magnitude of earthquake, source-to-site distance and site condition, respectively. Y_1 and Y_2 are resultant peak horizontal and vertical accelerations.

These rules may be triggered in different strengths based on the input data of the earthquakes and some of them may not be triggered. With the combination of the triggered rules, PGHA and PGVA were achieved through use of two fuzzy interface systems: Mamdani-type interface (Mamdani and Assilian 1975) and Sugeno interface system (Sugeno 1985). After several trial and errors on the output and with the focus on reducing the error in the predicted values, Sugeno-type interface was used for the final layout of the fuzzy logic model. For the defuzzification of the output, the weighted averages of all functions were applied.

From the total data of 316 acceleration records, 240 random data were used for training the model and remaining data were used for testing. To train the model to reach an acceptable acceleration, more than 8000 training were done to reach a constant error reduction of 5%. During training the model, membership functions of the magnitude and source-to-site distance were changed accordingly with the aim of lowering the ultimate error in such a way that the best match occurred in the outputs. Figure 2 shows the optimized membership functions for magnitude and source-to-site distance after training the model. Comparing the membership function in Figs. 1a and 2a, it can be seen that the peak of the membership function for moderate function was changed from $M=4$ to $M=5$, which shows that in the selected database, data with magnitude around 5 are more effective than those with magnitude 4 in prediction of the accelerations. For the membership function of source-to-site distance, this comparison shows that the membership function for the far field and intermediate field were increased and decreased, respectively; membership function for far field was strengthened and for the intermediate field was weakened.

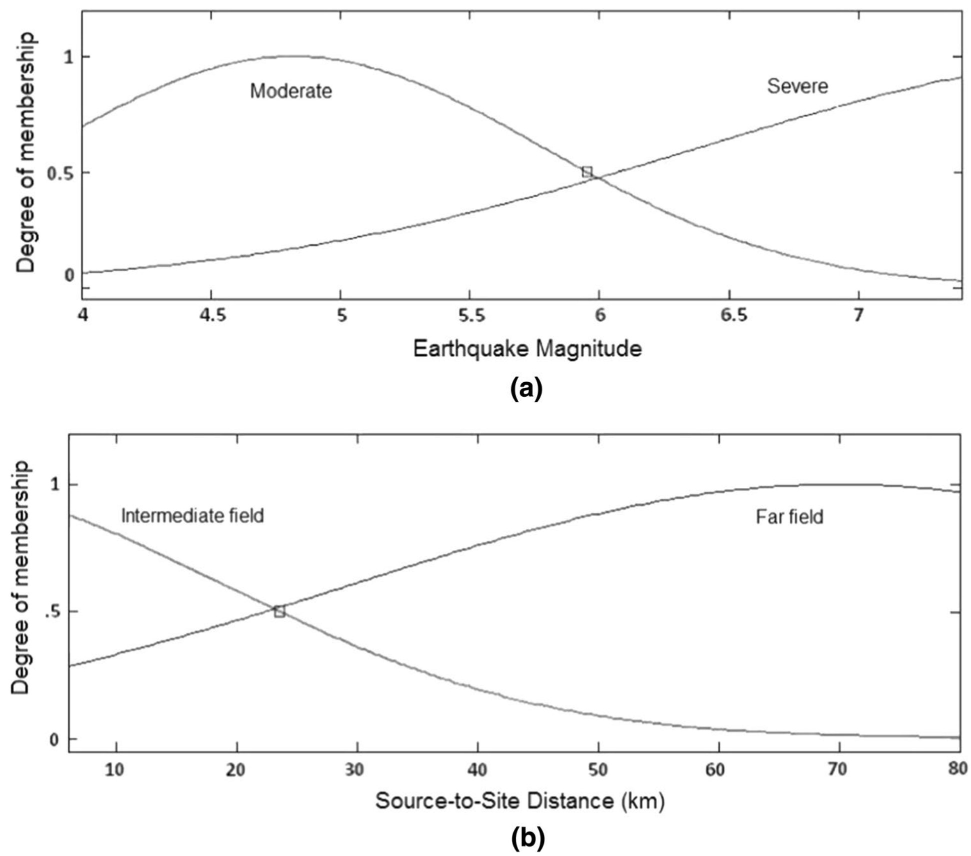

Fig. 2 Optimized membership functions for **a** magnitude of earthquake and **b** source-to-site distance

Evaluation of the model

All the input parameters have some uncertainty, but the most uncertainties occur in the site conditions and the source-to-site distance. Similar to the study by Ahumada et al. (2015), these uncertainties were not waived in this study, but a better and accurate approach was developed to address them.

In order to evaluate the performance of the model, predicted and measured values of PGHA and PGVA are shown in Fig. 3. As can be seen, the data in both peak accelerations are distributed along the line $Y = X$, which shows that predicted accelerations are close to observed accelerations. In order to evaluate the performance of the model quantitatively, coefficient of efficiency (CE) and global error in the model as root mean square error (RMSE) were used based on the following definitions:

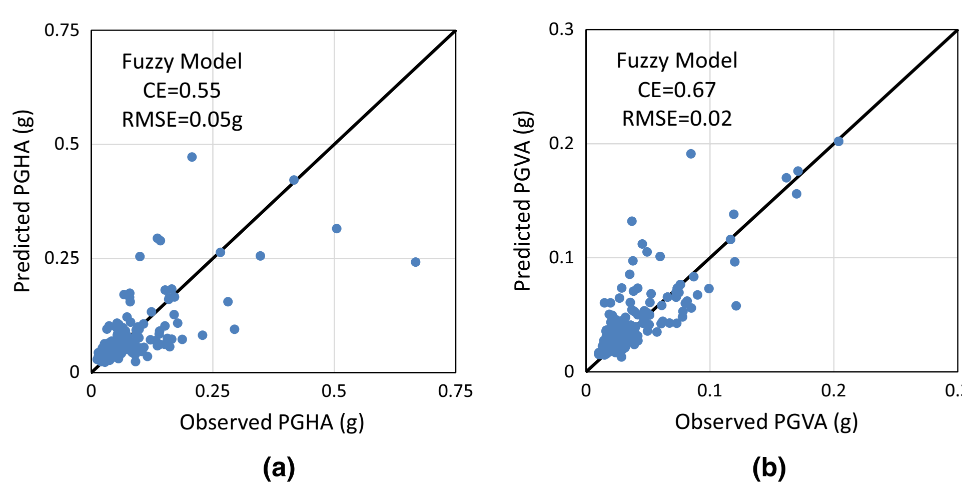

Fig. 3 Comparison between observed and predicted earthquake accelerations, **a** PGHA and **b** PGVA

$$\mathrm{CE} = 1 - \frac{\sum_{i=1}^{N} \left(a_{\mathrm{pi}} - a_{\mathrm{oi}}\right)^2}{\sum_{i=1}^{N} \left(\bar{a}_{\mathrm{o}} - a_{\mathrm{oi}}\right)^2} \quad (1)$$

$$\mathrm{RMSE} = \left(\frac{1}{N} \cdot \sum_{i=1}^{N} \left(a_{\mathrm{pi}} - a_{\mathrm{oi}}\right)^2\right)^{0.5} \quad (2)$$

where a_{pi}, a_{oi} and $\bar{a}_{\mathrm{o}}$ are predicted acceleration, observed acceleration and mean observed acceleration for the observation i, respectively. N is the total number of data.

Both CE and RMSE are presented in Fig. 3; due to a high discrepancy in the data, which usually exists in the earthquake input motions, the coefficient of efficiencies in both PGHA and PGVA is a little low, with a better accuracy in the vertical acceleration.

In order to compare the efficiency of the model with other attenuation relationships, two worldwide and three regional relationships were used; for the former, attenuation relationships developed by Boore et al. (1997), Ambraseys et al. (2005a, b) were selected and for the latter, the relationships presented by Amiri et al. (2007); Khademi (2002), Zare and Sabzali (2006) were used. The reason for selection of the worldwide attenuation relationships is first, because data from Middle East and Iranian plateau were used in the development of the relationships and second due to use of similar local site conditions as those in this study.

The results of the acceleration prediction with these attenuation relationships are shown in Fig. 4 in comparison with the fuzzy logic simulation. Figure 4a and b shows that there are high discrepancy in the observed and predicted accelerations in all attenuation relationships similar to fuzzy logic modeling, but the coefficient of efficiency in fuzzy logic model is better than those based on attenuation relationships.

For PGHA greater than 0.4 g almost all methods underestimate the horizontal acceleration, even fuzzy logic modeling; the reason for the former is the insufficient data for high accelerations. Among the attenuation relationship methods, the method presented by Amiri et al. (2007) has better results and its CE and RMSE are the same as those in the fuzzy logic model. RMSE as an overall error in all data is almost in the range of 0.05–0.06 g.

For PGVA, fuzzy logic modeling has a better result than the methods based on attenuation relationships. Methods presented by Zare and Sabzali (2006) and Ambraseys et al. (2005b) overestimate and underestimate the vertical acceleration, respectively, with low coefficient of efficiency. But there is no strong bias in other methods as well as in the fuzzy logic model. The deviation from the 45° diagonal line in the fuzzy logic model is less than methods relying on attenuation relationships, which results in higher CE and lower RMSE in the fuzzy logic model. These confirm that the efficiency and accuracy of the fuzzy logic model are better than those based on attenuation relationships.

Earthquake input motion characteristics in the model

An important contribution of the fuzzy system is its inherent capacity to capture nonlinear relationships (Ahumada et al. 2015) in the input–output set of data. As can be seen in the developed model, the complex relationship was set in the selected earthquake database. But does this model incorporate the fundamental aspects of attenuation relationships? Does the model capture the important characteristics of the earthquake motions? In this part, these important aspects are discussed for the developed fuzzy logic model to demonstrate how well the model is aligned with principles of seismic wave propagations.

An important aspect of modeling with intelligent systems is that if the selected data are appropriate, these models should show the engineering principles and mechanisms throughout the whole system without enforcing by additional rules. In order to control these specific aspects in this study, the trends of the output in connection with changes in the inputs are investigated. For instance, after training and testing the model and achieving an acceptable fuzzy model in the previous section, different values were entered in the model with different magnitudes and source-to-site distances on three different site conditions to see the changes in both PGHA and PGVA. Changes in the output with changes in the inputs were assessed to find their dependencies, which are shown in Fig. 5 for horizontal acceleration. It can be seen from these figures that with increasing the source-to-site distance of earthquake, the horizontal acceleration decreases, which is expected due to the geometrical spreading of the earthquake motions in the ground. Also in this figure, the increase in PGHA with the increase of earthquake magnitude is shown, which is compatible with the general concept of wave source generation.

The effect of site condition has also been captured by the fuzzy logic model. The results of the fuzzy logic model show that the peak accelerations in the stiff soil and soft soil conditions in all distances and earthquake magnitudes are higher than those in rock condition. Based on data from Mexico City and the San Francisco Bay area and several response analyses, Idriss (1990) showed that at low to moderate acceleration levels (less than about 0.4 g), peak acceleration at the surfaces of soil deposits are likely to be greater than on rock sites. This is in agreement with the results of the modeling in this paper, depicted in Fig. 5. In higher accelerations, opposite trends may happen in soft soils because of the dissipation of earthquake energy in soil layers due to their nonlinear behavior. However, the maximum predicted earthquake on

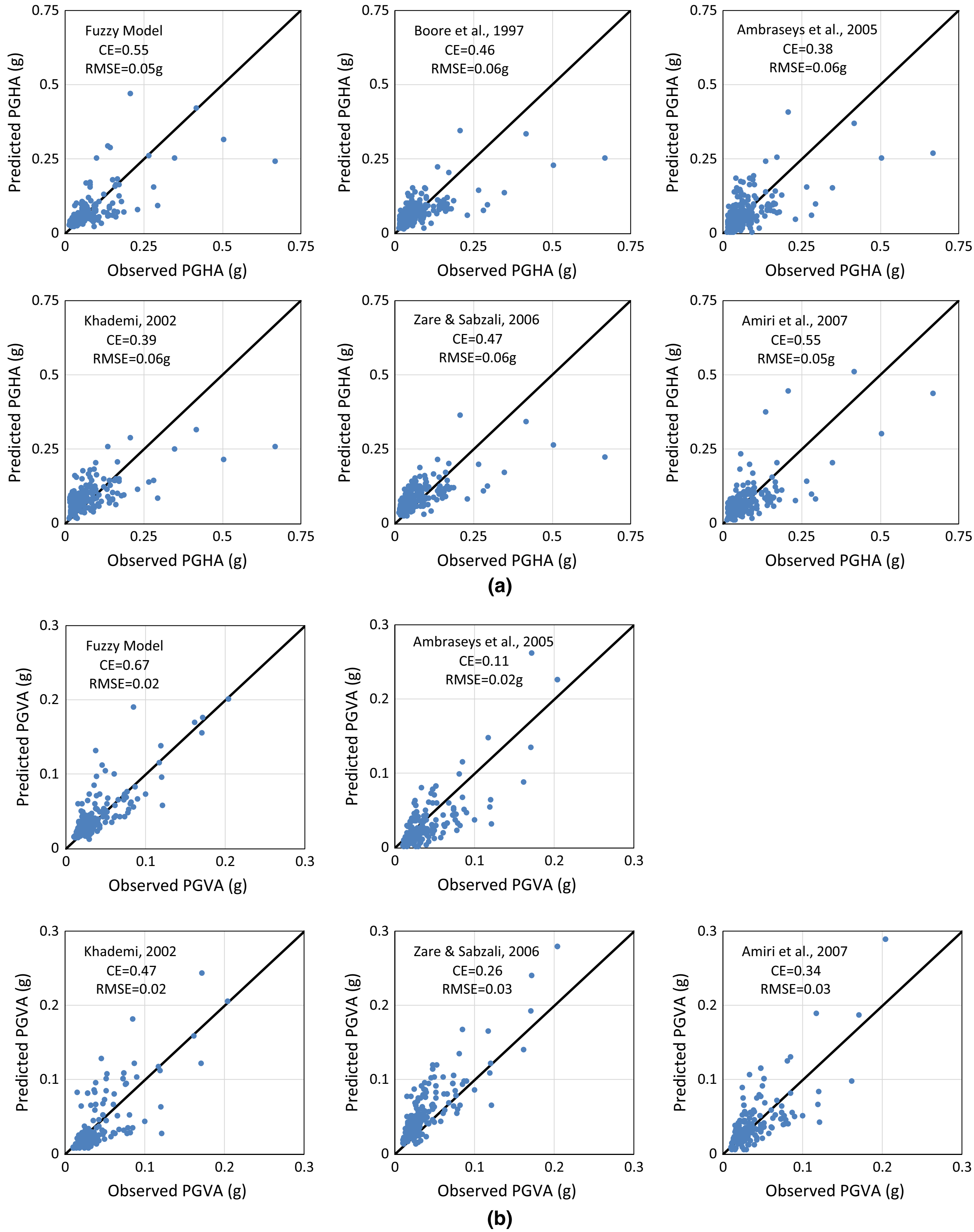

Fig. 4 Comparison between observed and predicted ground motion accelerations using fuzzy logic modeling and attenuation relationships **a** PGHA and **b** PGVA

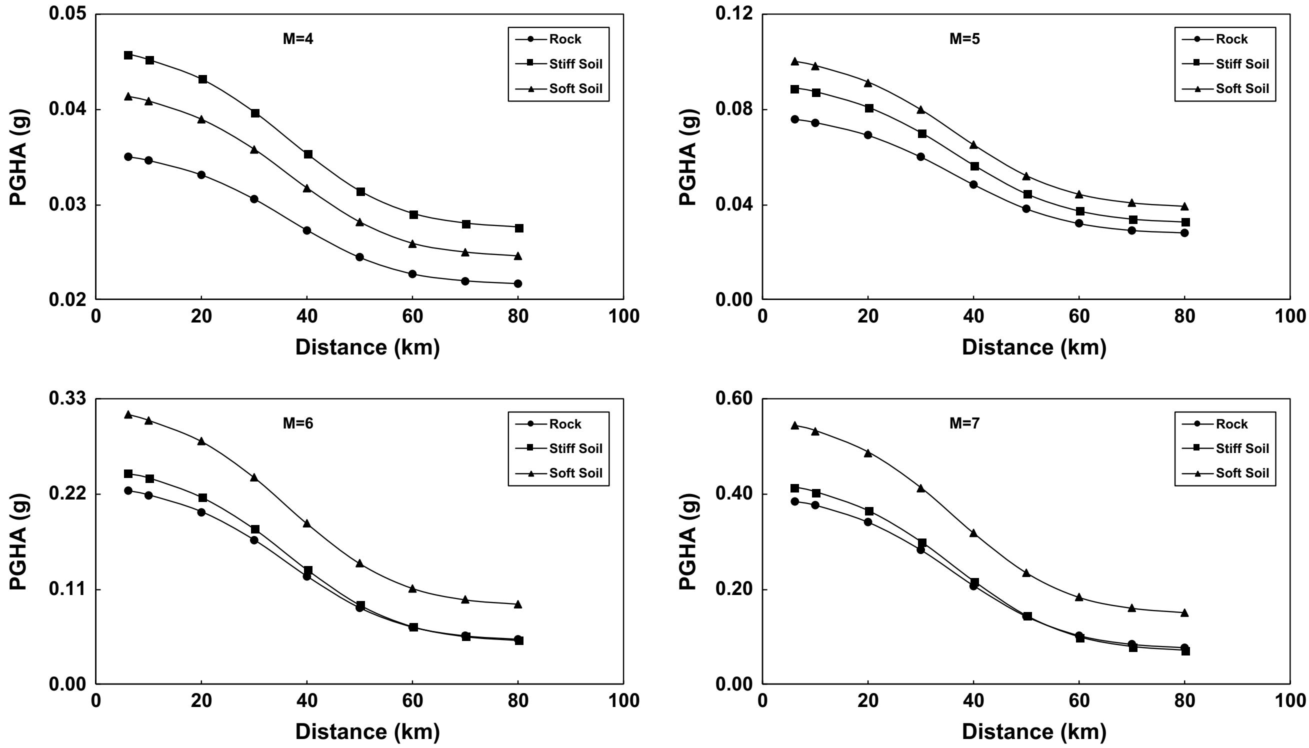

Fig. 5 Variation of peak ground horizontal acceleration with earthquake magnitude and source-to-site distance in different site conditions

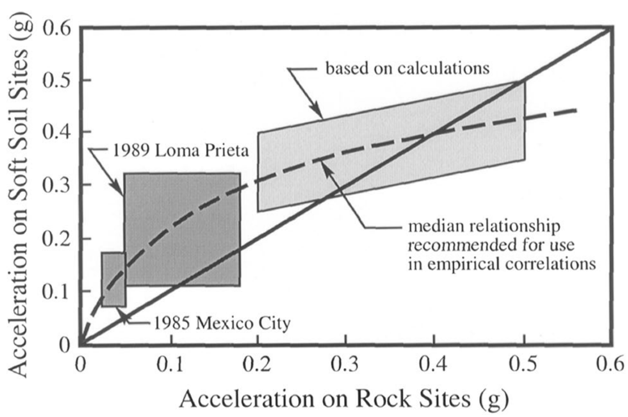

Fig. 6 Approximate relationship between peak accelerations on rock and soil sites (Idriss 1990)

rock sites in the fuzzy logic model even in the magnitude of 7 is around 0.4 g. Comparing with the results of the ground response analysis by Idriss, in these range of accelerations, both increase and decrease in peak ground acceleration on soils are possible (Fig. 6).

Changes in peak vertical acceleration with source-to-site distance for four values of earthquake magnitude and different site conditions are shown in Fig. 7. As can be seen on these graphs similar to horizontal accelerations, vertical accelerations reduce by increasing the distance and decreasing the earthquake magnitude.

Similar to horizontal acceleration, site conditions affect the values of vertical acceleration. It can be seen from Fig. 7 that vertical accelerations in rock sites in all distances and in all earthquake magnitude are less than those in soil sites, which is in agreement with Idriss's study mentioned before. This is the result of local site condition, which can influence all important characteristics of strong ground motion such as duration, frequency content and amplitude. The effect of local site condition can be illustrated in several ways: by theoretical ground response analyses, by measurement of ground surface motions from different sites with different subsurface conditions and by measurement of actual surface and subsurface motions at the same site, but in general softer soil will amplify low-frequency (long-period) bedrock motions more than stiffer soil and the reverse would be observed for high-frequency motions (Kramer 1996).

In order to see the change in the acceleration due to the change in the earthquake magnitude, PGHA and PGVA for the source-to-site distance of 35 km are presented in Fig. 8. The trend shows that with an increase in the earthquake magnitude, both PGHA and PGVA increase; the former in an S-shaped curve and the latter with increasing rate. This picture also shows the increase in the peak accelerations in the soil sites in comparison with rock sites.

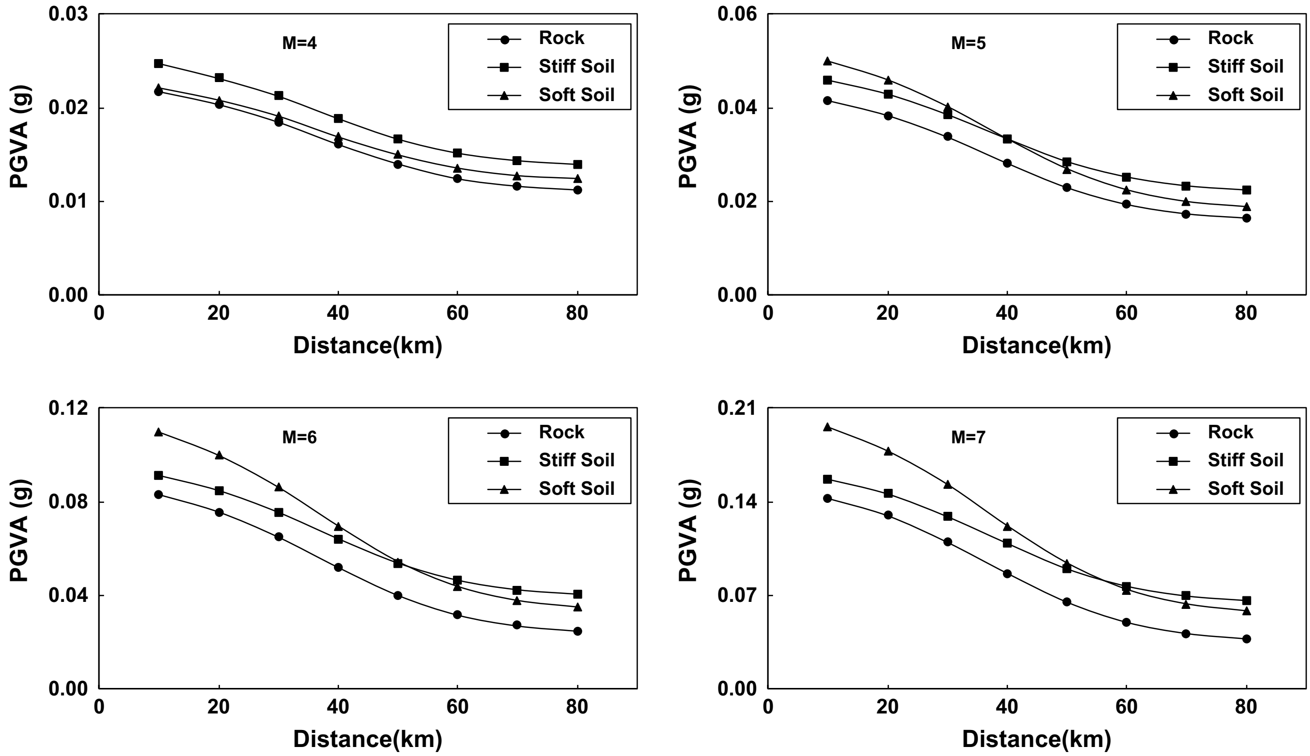

Fig. 7 Variation of peak ground vertical acceleration with earthquake magnitude and source-to-site distance in different site conditions

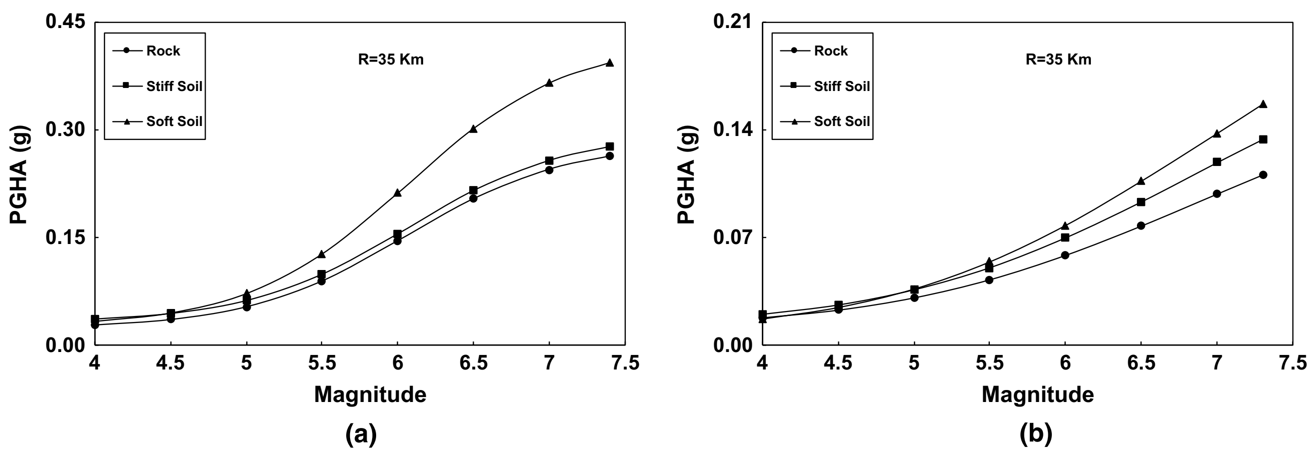

Fig. 8 Changes in horizontal and vertical acceleration at the distance of 35 km

Changes in horizontal and vertical acceleration at two different magnitudes of 4 and 6 for the rock site condition are shown in Fig. 9. Reduction in the acceleration in both PGHA and PGVA is shown in these curves. Results show that differences between horizontal and vertical acceleration in higher magnitudes are more considerable than lower magnitudes, especially when distance is lower than 40 km. In the lower magnitude ($M = 4$), difference between PGHA and PGVA remains constant up to almost 40 km.

The above discussion shows that important characteristics of earthquake motion are modeled via fuzzy logic model; reduction of peak ground acceleration with an increase in the source-to-site distance and decrease in the magnitude of the earthquake and effect of site conditions on the magnification of input motion. Therefore, the developed fuzzy logic model captures these characteristics without enforcing them via additional equations; enforcing is inherited by the input data.

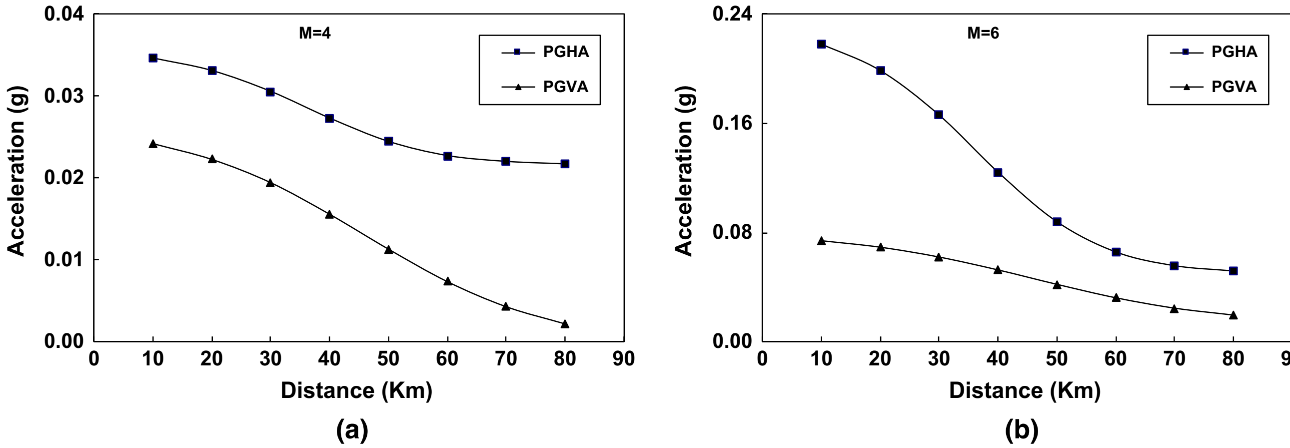

Fig. 9 Changes in the PGHA and PGVA in rock site condition at magnitudes of 4 and 6

Comparison with other attenuation relationships

In Fig. 4, peak ground accelerations from the fuzzy logic model are compared with those from different attenuation relationships. In this section, the results of the fuzzy logic model are compared with these methods considering the concept of attenuation relationships; for instance, the simulation was done with a constant magnitude of 5 and 7 for the local site conditions of soil and rock with various source-to-site distances. In Fig. 10, curves of PGHA and PGVA versus distance from fuzzy logic modeling are compared with those from the study by other researchers. Figure 10a shows that the developed fuzzy logic model has a tendency in presenting higher PGHA at the high earthquake magnitudes in the site-to-source distance less than 40 km, regardless of the site condition; the results of the fuzzy model in this condition in long distances are almost in the range of other relationships. For PGHA in lower magnitudes, the tendency of the model is lowering the acceleration in the shortest distance. These alterations of the fuzzy logic from other methods are most probably due to the lack of regional acceleration data in high magnitudes and low distances.

Figure 10b shows that attenuation relationship for PGVA from fuzzy logic modeling is almost in the range of acceleration from traditional attenuation relationships, except for the data at high magnitudes and low distances, in which fuzzy logic gives an underestimated result. Again this is due to insufficient acceleration data in these ranges of inputs.

The above discussion shows that when there are no sufficient data in some areas of the strong database, the results of modeling will be overestimated or underestimated and care should be taken to apply the method for practical purposes. One way to reduce the lack of data in the input motion could be the use of data from other areas on Earth, which has the same seismotectonic characteristics and site conditions as the selected regional area.

As can be seen in Fig. 10, different ground motion models give a different value for the peak ground accelerations and the differences between peak accelerations are high in both worldwide and regional attenuation relationships. Because of these uncertainties in these models, logic tree method is recommended as a framework for the explicit treatment of model uncertainty (Kramer 1996). Instead in the fuzzy logic model, the attenuation relationship is developed based on previous data in the regional area and regional ground motion characteristics are inherited in the model.

Discussion

In traditional approaches for development of attenuation relationships, with regression analysis on all data, a formula is obtained based on theoretical and empirical assumptions. But in a fuzzy system each of the input data has its own weight and validity on the output. Because of the dynamic nature, fuzzy logic modeling is more flexible in predicting the acceleration. Furthermore, on the fuzzy logic model for peak ground acceleration, the uncertainty of data is considered automatically, which changes from one data to another data. Therefore, each output has its own special and separate uncertainty, and because of this fact, a complex relationship between accelerations and input parameters can be established.

The results of this study showed that the efficiency of the fuzzy logic model is higher than the regional and worldwide attenuation relations for prediction of acceleration (Fig. 4). The efficiency in PGVA is even higher. This is probably because the effect of individual data is considered naturally in the fuzzy logic model. Along with the fuzzy logic model, the accuracy of the prediction by regional attenuation

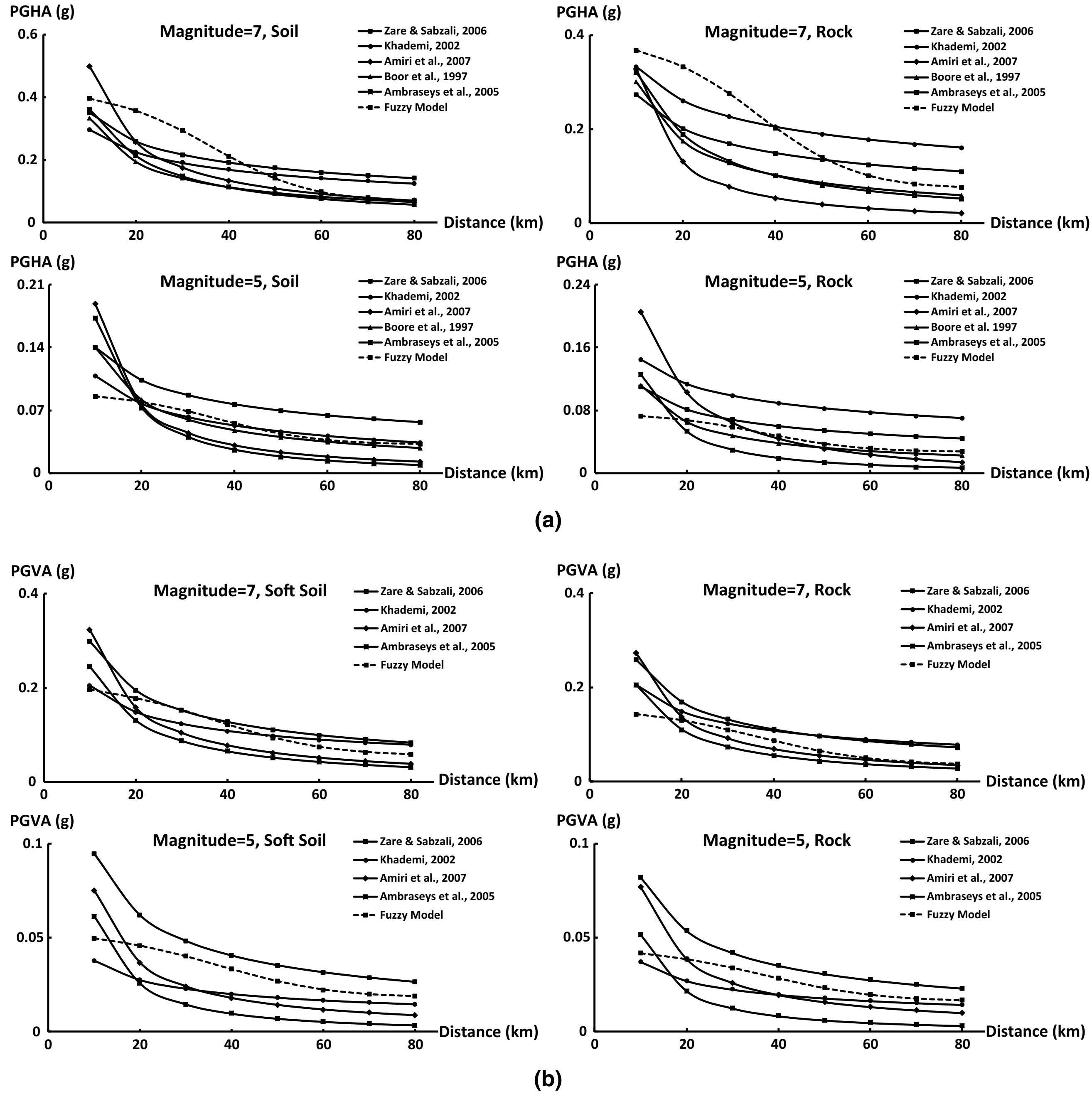

Fig. 10 Curves of peak ground accelerations versus distance for magnitude 5 and 7 in soil and rock sites, **a** PGHA and **b** PGVA

relationships is generally higher than worldwide attenuation. This is because in the formula for the local attenuation relations such as those developed by Khademi (2002), Zare and Sabzali (2006) and Amiri et al. (2007), the data from Iranian Plateau were used with the same site conditions. However, in other attenuation relationships, data of various seismotectonic environments was employed. In the relationship developed by Ambraseys et al. (2005a, b), data from Europe and the Middle East were used; although this covers Iranian plateau, the discrepancy in its results is higher than regional attention relationships and fuzzy model. The accuracy of the results from the attenuation relation developed by Boore et al. (1997) is a little better, while data from western North American earthquakes were used in its development. This means that in addition to the worldwide attenuation relations, regional attenuation relations such as the one developed in this study should be applied.

One issue with the implementation of the fuzzy logic theory is the number of data selected for the prediction. In this study for estimation of ground motion acceleration in

Iranian Plateau, the number of data was limited to the number of records from earthquake events in the region. In fact, the developed model for attenuation relationships works only in this region and cannot be used in other area on Earth. Distribution of the input data is another shortcoming of the fuzzy logic models for earthquake input motions, which is inherited in the earthquake data. More data are available for earthquake input motions with lower magnitudes due to its high frequency of occurrence. In the current paper, 20% of the data have magnitude greater than 5.5. This means that accuracy of the model for earthquake events more than 5.5 magnitude is lower than the rest of them. This is because in the fuzzy logic model more data have been used for training within the range of 4–5.5 magnitude. For the worldwide attenuations, quite a few earthquake acceleration histories are available (e.g., in PEER earthquake database) due to the number of earthquake recorded across the world. However, the number of ground motion records is increasing due to recording new earthquakes. The benefit of the developed model is the fact that new data can be added to update the model. In fact, this is the flexibility of the fuzzy logic model, which benefits users to advance the attenuation model.

Conclusions

In this study, a fuzzy logic model was developed to predict peak ground horizontal and vertical earthquake accelerations inside Iranian plateau. Input parameters were earthquake magnitude between 4 and 7.4, source-to-site distance from 7 to 80 km and local site conditions of rock, stiff soil and soft soil. Comparison between predicted and observed accelerations showed an acceptable level of acceleration prediction for both PGHA and PGVA, especially in the far field. In the developed fuzzy logic model, the uncertainty of earthquake ground motion records was accurately simplified by implementing only a few of motion parameters.

In order to evaluate the accuracy of the fuzzy logic model in presenting basic characteristics of earthquake wave propagation, a parametric study was conducted; it was shown that trends of the PGHA and PGVA with changes in earthquake magnitude, source-to-site distance and local site conditions are meaningful with respect to ground motion characteristics. These were not implemented in the fuzzy logic model as additional rules, but overall rule were achieved from the input–output data. These basic characteristics are:

- With an increase in the distance and a decrease in the magnitude, both horizontal and vertical accelerations decrease, which is in agreement with the concept of geometric spreading and anelastic attenuation.
- In the ranges of data used in this study, the peak ground acceleration in soil sites are more than rock sites.

The comparison between the attention relations showed that the attenuation curves from the fuzzy logic model were in the range of regional attenuation relations for large distances. This is probably because the data from the same seismotectonic environment have been used. The attenuation relations for PGHA developed by the fuzzy logic model were also comparable with those developed by worldwide formula. However, PGVA from worldwide formula (Ambraseys et al. 2005a, b) was lower than the fuzzy logic model and other regional attenuation relations. A possible explanation for this might be that other seismotectonic environments were used in the worldwide formula. Attenuation curves from the fuzzy logic model for the near field acceleration deviate from other relations, which is probably due to the lack of data in the near field.

Overall, the results of the study confirm that new methods based on fuzzy logic theory can be used for improving and developing attenuation relations and predicting both PGHA and PGVA for engineering applications. However, various physics-based GMPEs suffer from a satisfactory number of records of large earthquakes ($M > 6.5$), especially in the near field ($R < 10$ km). The method applied in this study can give more reliable and robust results, provided that the data set used exhibits satisfactory distribution in magnitude, distance and soil conditions.

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