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Peak ground acceleration attenuation relationship for Mazandaran province using GEP algorithm

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Abstract. The choice of attenuation relationships is one of the most important parts of seismic hazard analysis as using a different attenuation relationship will cause significant differences in the final result, particularly in near distances. This problem is responsible for huge sensibilities of attenuation relationships which are used in seismic hazard analysis. For achieving this goal, attenuation relationships require a good compatibility with the target region. Many researchers have put substantial efforts in their studies of strong ground motion predictions, and each of them had an influence on the progress of attenuation relationships. In this study, two attenuation relationships are presented using seismic data of Mazandaran province in the north of Iran by Genetic Expression Programming (GEP) algorithm. Two site classifications of soil and rock were considered regarding the shear wave velocity of top 30 meters of site. The quantity of primary data was 93 records; 63 of them were recorded on rock and 30 of them recorded on soil. Due to the shortage of records, a regression technique had been used for increasing them. Through using this technique, 693 data had been created; 178 data for soil and 515 data for rock conditions. The Results of this study show the observed PGA values in the region have high correlation coefficients with the predicted values and can be used in seismic hazard analysis studies in the region.

Keywords: attenuation relationship; genetic expression programming; earthquake; mazandaran

1. Introduction

Iran is located in the Middle East and it is one of the most seismically active countries. It is situated on Himalyan-Alpide seismic belt, which is one of the most active belts over the world (Ghodrati *et al*. 2007). Consequently, the importance of estimating the seismic hazard can never be overlooked in Iran. On the other hand Alborz seismic zone in which located in the north of Iran, is one of the most seismic zones in the country. There are some provinces in the Alborz seismic zone including Mazandaran. According to evidences, there are some active faults in Mazandaran which are the main cause of earthquake in this northern province (Taleshi and Jahani 2017). Khazar fault is the most active fault in the region (Nemati *et al*. 2013). Some destructive earthquakes have occurred in Mazandaran during the history. For instance, Farim in 1127, Farim in 1301, Haraz in 1825, Kesout in 1935, Bandepey in 1957 (Ambraseys and Melville 1982, Ambraseys 1974).

Dynamic analyses of structures need different earthquake parameters, such as base design acceleration and design spectra. In order to obtain these parameters of a site, current methods are generally based on seismic hazard analyses. Applying different attenuation relationships depends on seismic behavior of the considered area (Ghodrati *et al*. 2015, Joshi and Midorikawa 2005). Decreasing the amplitude of seismic waves with increasing the site to source distance is referred to seismic wave attenuation (Ma'hood and Hamzehloo 2009). A deep understanding of the attenuation features of seismic ground motions is an important step in the logical design of structures and infrastructures at the specific site (Safari *et al* 2012). Because a large percentage of uncertainties in obtaining different earthquake parameters refer to uncertainties is seismic wave attenuation (Farrokhi and Hamzehloo 2017). Many parameters have significant influences on the attenuation of the earthquake waves. For example, the site distance, type of the soil and earthquake magnitude. In seismic hazard analyses, the base design acceleration and design spectra are obtained from seismicity of the region and the site conditions based on probabilistic statistical methods. This method also requires attenuation relationships for different parameters of an earthquake. The attenuation models are able to indicate a particular ground-motion parameter, like spectral acceleration attenuates with varies distances and different earthquake sizes. (Ghasemi *et al.* 2009). The most common parameters are peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD) and the spectral specifics. This study considers the attenuation relationships for the PGA in Mazandaran province in the southern part of the Caspian Sea.

The basic form of the ground motion prediction equation (GMPE) can be defined as Eq. (1) (Ambraseys and Bommer 1991)

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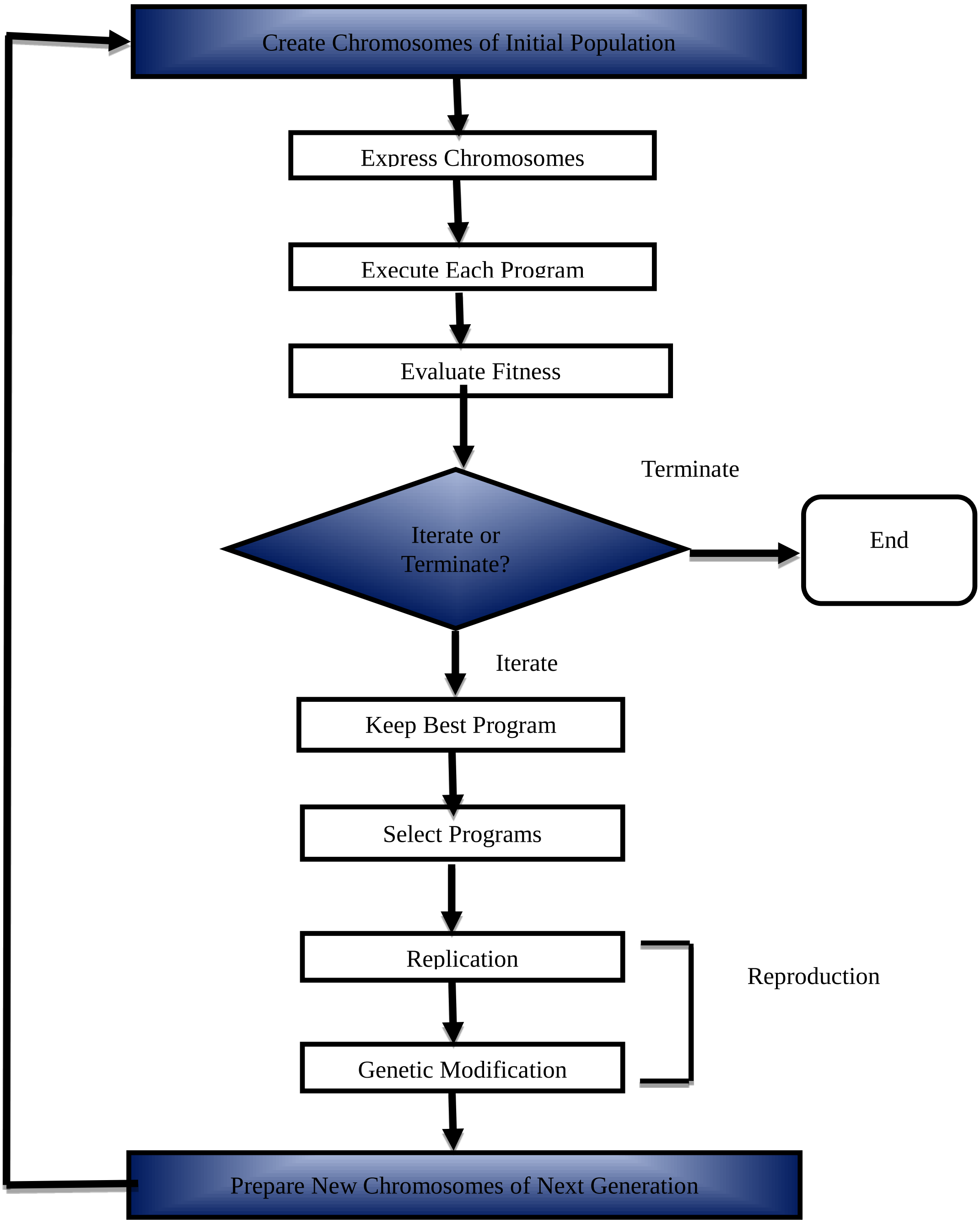


Fig. 1 Fundamental steps of Gene Expression Programming (Ferreira 2006)

$$Ln(A) = C + f(m) + f(r) + f(soil) + \varepsilon \tag{1}$$

Where A is strong ground motion parameter (e.g., Peak acceleration), C is a constant scaling factor, f (m) is a function of independent variable M (magnitude), f (r) is a function of independent variable R (shortest distance from the station to the source), f (soil) is a function of the type of the soil.

Although the first attenuation relationship was presented by Neumann in 1954 (Neumann 1954), the first attenuation relationship which was specifically for Iran, had been presented by Zare (1999). After his research, a number of researchers attempted to present suitable attenuation relationships for the Iranian Plateau (Nowroozi 2005, Ghodrati *et al.* 2007, Zafarani *et al.* 2008, Saffari *et al.* 2015, Yazdani *et al.* 2015, Soghrat *et al.* 2016, Mahmoudi *et al.* 2016). They usually separated Iran into two major seismic zones; Zagros and Alborz. In passing time and the progression of the technology, computers have assisted engineers which have resulted in fundamental changes to the predictive ground motion models. One of these progressing was creating GEP algorithm. Cabalar and Cevik (Cabalar and Cevik 2009) presented a new attenuation relationship using this new algorithm for Turkey. Also, Ghodrati and Shamekhi (2014) had some efforts in investigating on the new ground motion model using GEP in Iran too. Moreover, Jafarian *et al.* (2010) presented an empirical prediction model for the $v_{\max}/a_{\max}$ ratio of earthquakes using genetic programming. In this paper, we have developed a new ground motion prediction equation (GMPE) for Mazandaran, Iran, using the GEP algorithm.

2. Seismotectonic

The crust of the earth consists of plates which are always in a slow movement. On the other hand, the borders of adjacent plates have interlocks that can sustain a stress. The slow motions of adjacent plates cause rocks to strain. When this stress becomes greater than the rock's strength, the rocks can suddenly break and a strong ground motion happens.

Researchers proved that geometrical influences associated with uninterrupted distributed deformation originate features of the tectonic plates of Iran (Jackson *et al.* 1995). The structure of the Alborz range resulted from some tectonic collisions in the Triassic period (Şengör 1988). The Alborz mountain belt is located in north of Iran and south of the Caspian Sea. This belt is 100 kilometers wide and something about 600 kilometers long (Maleki *et al.* 2013). The average higth in Alborz seismic zone changes from 5588 to -53 and decreases from the south to the north. (Amiri and Conoscenti 2017). The thickness of crust is about 40 Kilometers in the northern part of the Alborz mountain belt (Afsari *et al.* 2015). Evidences show that the south of the Caspian Sea is an active seismic region (Abbassi *et al.* 2010). Some of the most important faults in the Alborz seismic zone are Khazar fault, North Alborz fault, North Tehran fault, North Qazvin fault, Alamutrud fault, Mosha fault and North Tabriz fault (Abdollahzadeh *et al*. 2014, Khoshnevis *et al*. 2017).

Mazandaran province is located in the central Alborz seismic zone that consists of a lot of parallel anticlines and synclines, which shaping the southern border of Caspian Sea (Riazi Rad and Javan Doloei 2009).

3. Methodology

Genetic algorithm (GA), a method based on Darwin's evolutionary algorithm, was made by John Holland in 1960 and developed by Koza (1992). He used computer systems to simulate biological evolutionary theory. In GA, a problem is defined in fixed length strings of 0's and 1's coding, and then genetic operators are done on these strings until a best solution according to fitness be selected. In other words, a GA population contains a plenty of individuals to evolve under specified selection laws to reach maximum fitness. The fitness of each individual in GA shows that the individual has been adapted to the problem (Cevik and Cabalar 2009). Later, derivations based on GA came to the forefront. Genetic Programming (GP) is development of GA, in which instead of using 0 and 1 coding, diagrams like tree called parse tree in different size and shapes are used. Like a genetic algorithm, GP produces some populations randomly, but defines them on the parse tree, then specify a fitness function that based on, the best solution can be reached (Koza 1995). All genetic operators, such as mutation, crossover and inversion are done with PT (Ferreira 2001). Generally, the GP phases can be explained as follows (Sarıdemir 2010):

1. Defining collection of input and output variables.
2. Defining a collection of specified mathematical functions in regression problems and Boolean functions in classification problems, for creating hypothetical and primitive relationship between input and output variables.
3. Selecting a fitness function as a measurement for solutions and controlling the propriety of obtained solutions.
4. Selecting some genetic operators and constants.
5. Selecting some statistical parameters for controlling and ending the run and showing the accuracy of modeling.

GEP is a kind of evolutionary algorithms with fixed linear chromosomes, such as genetic algorithms and expression trees of different sizes and shapes such as genetic programming. The chromosomes are built from multiple genes. The fundamental steps of Gene Expression Programming are schematically displayed in Fig. 1. The process is done more and more until a good solution has been found (Ferreira 2006). In GEP, all genes of the same sizes are coding in expression trees (ETs) of different sizes. All problems in GEP are presented by ETs which include operators, functions, constants and variables.

The GEP proposes many advantages as compared with other classical regression techniques. One of the advantages of GEP approach is that genetic diversity can easily be created because genetic operation works at the chromosome level (Calabar and Cevik 2011). Some functions define in advance in regression techniques where analyses of these functions are later performed while no predefined function is considered for the GEP approach. It is believed for modeling and obtaining clear formulations of experimental studies, like multivariate problems, GEP is more powerful than regression techniques and neural networks (Ganguly *et al*. 2009, Nazari and Riahi 2011, Bhargava 2011, Podgornik 2011, Milani and Nazari 2012, Abdollahzadeh *et al.* 2016, Abdollahzadeh *et al*. 2017).

4. Database and processing

For presentation of attenuation relationships, a comprehensive catalogue of peak ground acceleration, distance, depth and magnitudes are required. In this study 93 records from 22 earthquakes which recorded from 1975 to 2017 in Mazandaran province are used. 30 records of all, were recorded at sites with shear wave velocities less than 375 $\frac{\mathrm{M}}{S}$ that we call them soil and 63 of them, were recorded at sites with shear wave velocities more than 375 $\frac{\mathrm{M}}{S}$ which we call them rock. Red pints in Fig. 2 show the situations of the chosen earthquakes. There is no any earthquake record before 1975 in the region. All of the records have moment magnitudes more than 4. Smaller magnitudes have been cut from the catalogue because such earthquakes do not have significant influence on the structures in engineering problems. The biggest magnitude which exists in the catalogue is 6.4 related to Baladeh earthquake. The nearest accelerogram had been recorded with a distance of 6 kilometers from the source and the furthest record had 178

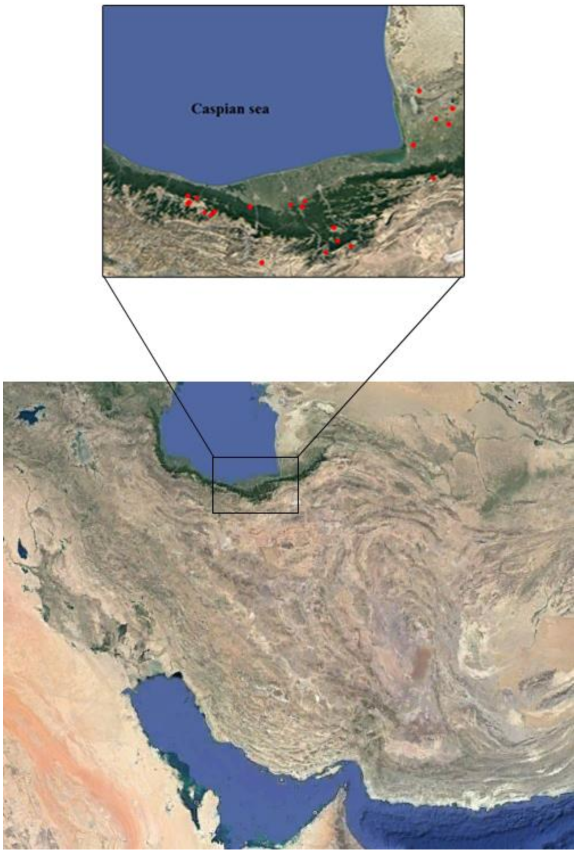


Fig. 2 Situation of chosen earthquakes

kilometers distance from the source to the station. Fig. 3 illustrates some information about variation of a number of records, moment magnitude, distance and site conditions. The data have been gathered from the Building and House Research Center (BHRC) in Iran. It would noticeable to mention that all of the used records had been corrected by BHRC. Every seismic station records three components of earthquake waves which consist of two horizontal waves and one vertical. In this paper, we used the maximum of the horizontal components of each record as the horizontal component of that one.

Since the quantity of data is few in the region, we used a regression technique for improving the condition. In this technique, at the first step, all records with same magnitudes had been separated. Then for each single magnitude, a power regression had been done by EXCEL software. Then the regression-trendline had been divided for everyone single kilometer and finally the PGA of each divided point had been read and considered as PGA at that distance.

For example, in the case of moment magnitude 4.5, the nearest data was recorded from 6 kilometers and the furthest was recorded from 66 kilometers. As shown in Fig. 4, at first there were just 4 records with magnitudes 4.5 on rock. By using this technique, 61 data sets had been created from 6 to 66 kilometers. However, these were just 4 real records in the catalog. Fig. 4 shows the power regression related to the magnitude 4.5 on rock. This technique had been repeated for all of the magnitudes which there were more than 3 records in the catalogue. Finally, 178 data had

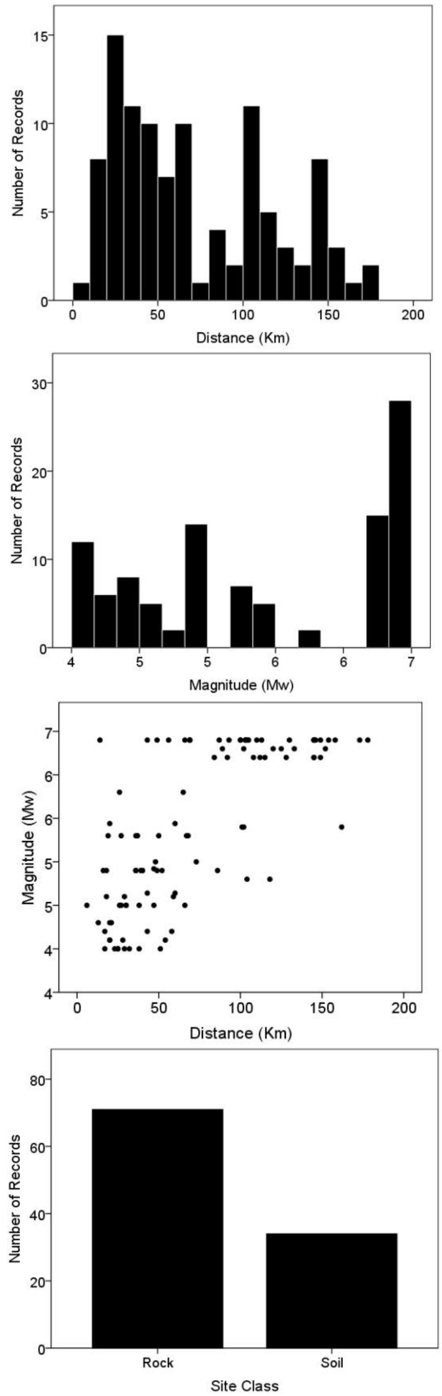


Fig. 3 Distribution plot and histogram of records versus distance, magnitude and site class

been created for soil and 515 data had been created for rock.

5. Results

Table 1 gives information about the models estimated in the current study. As it is clear from the table, there are two different attenuation models for two major site conditions named soil and rock. Each of them has 3 genes which are linked to each other by addition function. The expression trees have been shown in Fig. 5. R-square values, as one of

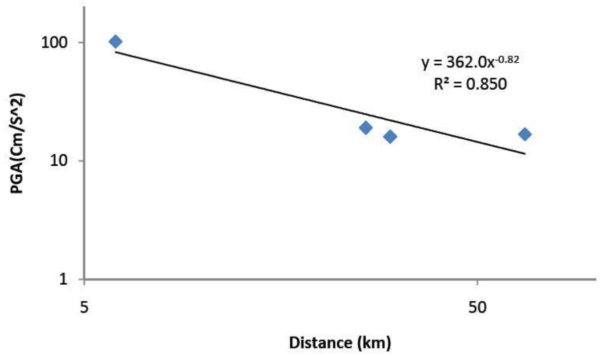


Fig. 4 The power regression plot in the magnitude of 4.5

the most important criteria to examine the accuracy of analysis was 0.866 and 0.978 for soil and rock conditions respectively.

For validation of presented attenuation relationships, two examinations have been performed. Firstly, the results of the presented attenuation relationships in this investigation were compared with five other existed relations for the Alborz seismic zone. Figures 6 and 7 illustrate the results of these comparisons for moment magnitudes 5.4 and 6.4 for rock and soil site conditions respectively.

As had been shown in Figs. 6 and 7, Nowrouzi's model tends to smaller PGA in most cases. Also Ghodrati's attenuation relationship results in bigger values for PGA, especially in far distances. The exemption is in the soil condition and moment magnitude 6.4, in near distances which GEP model outcomes bigger PGA. Although in less powerful earthquakes the presented equations in this study may not have very special notes to mention, because the PGA values are between other models in the region, they have plenty of notes to say in bigger earthquakes. It is obvious at the first glance that GEP model tends to be higher than other equations in such earthquakes especially

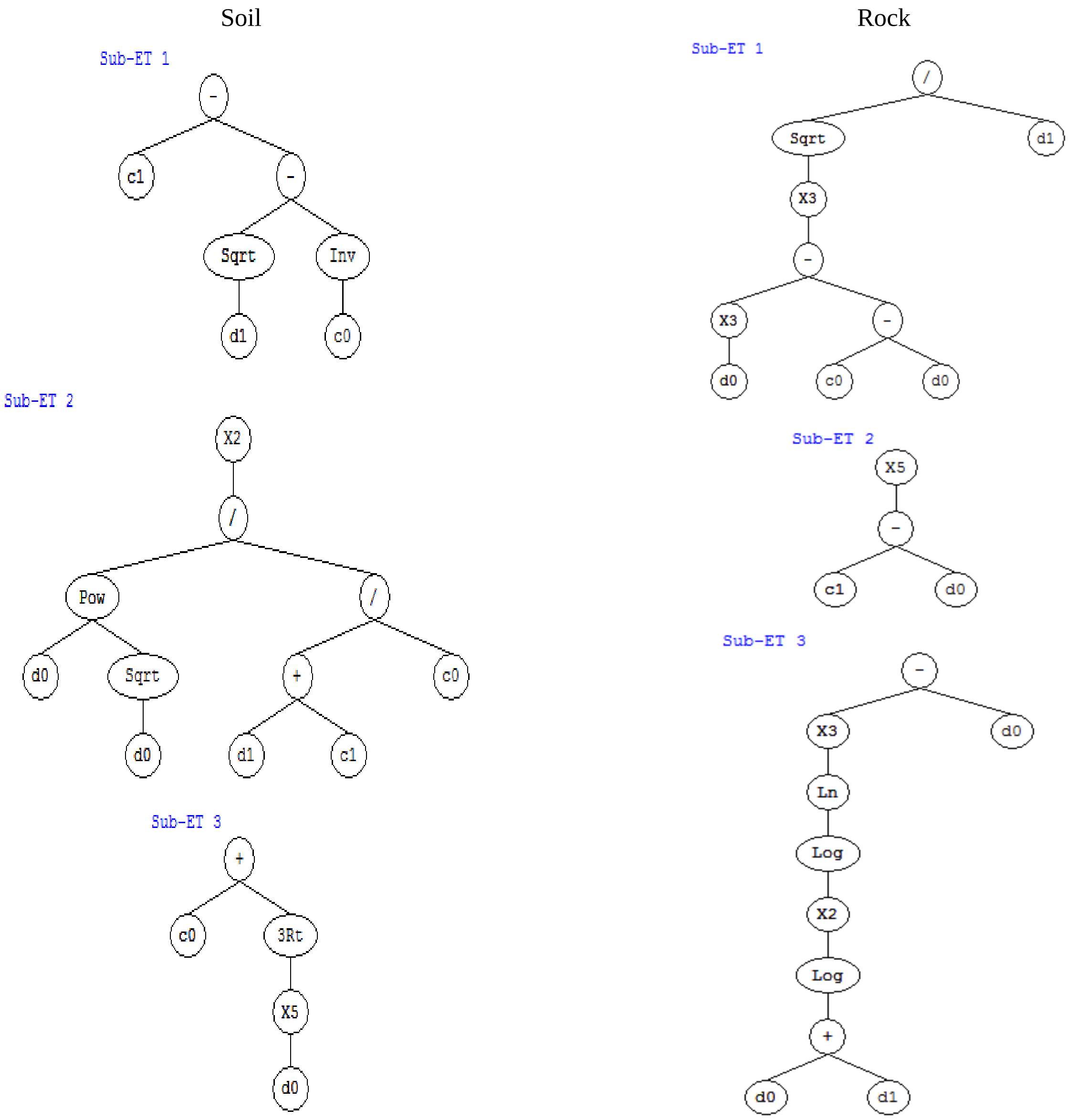
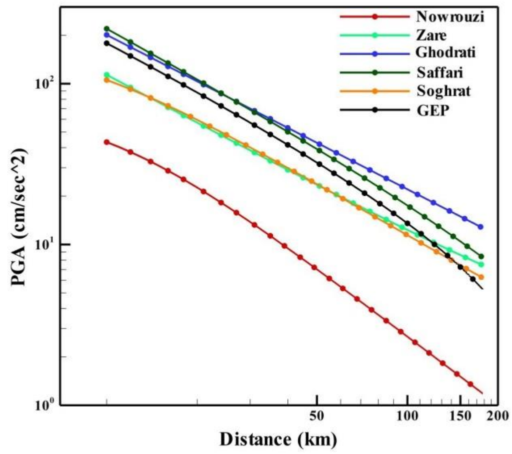


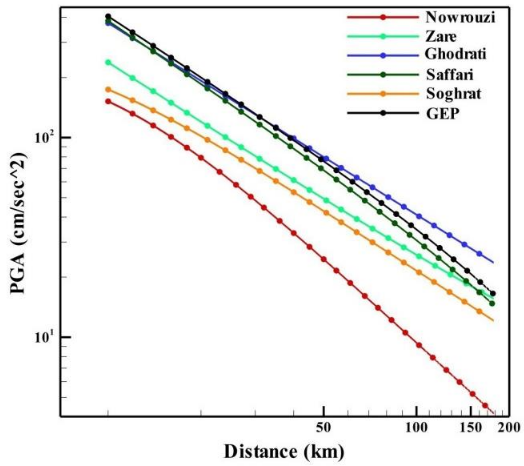
Fig. 5 Expression tree (ET)

Table 1 Presented attenuation relationships using GEP

Site Condition	Model
Soil	$PGA = \left(4.47 - \sqrt{R} + \frac{1}{3.83}\right) + \left(\frac{\frac{M_w\sqrt{M_w}}{R+6.44}}{3.25}\right)^2 + \left(2.17 + \sqrt[3]{M_w{}^5}\right)$
Rock	$PGA = \frac{\sqrt{\left((M_w{}^3 - (9.16 - M_w))\right)^3}}{R} + \left(5.49 - M_w\right)^5 + ((Ln(Log(Log(M_w + R)^2))^3) - M_w)$

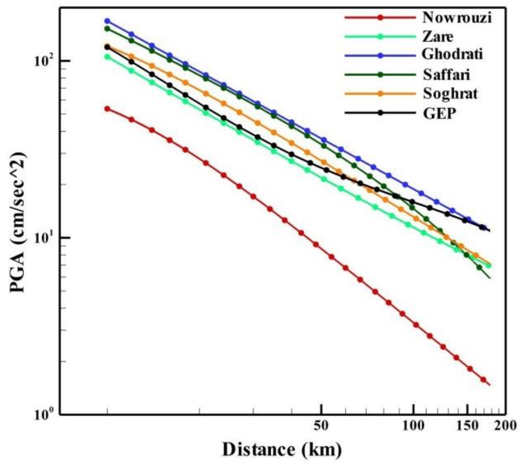


(a)

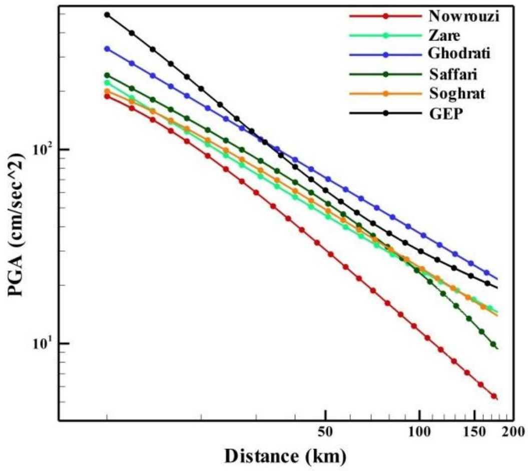


(b)

Fig. 6 Comparison between the presented model in rock site class for magnitudes of (a) 5.4, (b) 6.4



(a)



(b)

Fig. 7 Comparison between the presented model in soil site class for magnitudes of (a) 5.4, (b) 6.4

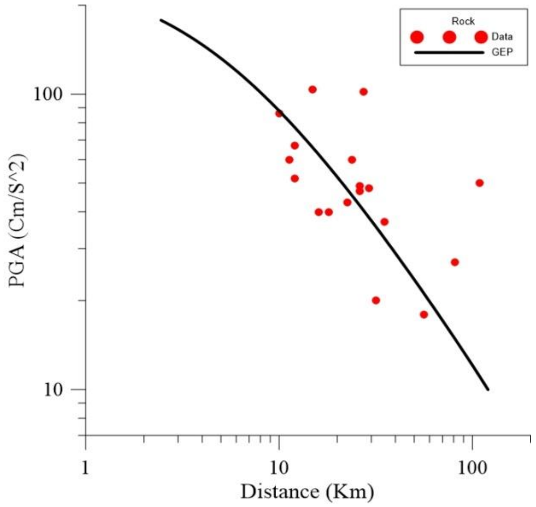
in near distances. Fig. 7(b) shows that the GEP model is much more critical than others in the first 30 kilometers. Although it would not eye-catching, a similar behavior is valid in Fig. 6(b). But in the mentioned figure, Ghodrati's and Saffari's models are very close to GEP model.

For the second validation of the relations, final results had also been compared with the main data of the earthquakes in the region. This was because to examine the compatibility of the model with primary earthquake data existed in the region. In this step, all of the data with moment magnitude 5 ± 0.5 had been shown with the result of the presented attenuation relationships for moment magnitude 5. The results of this comparison are shown in the Fig. 8. It can be observed that the new model shows a reasonable agreement with the main data.

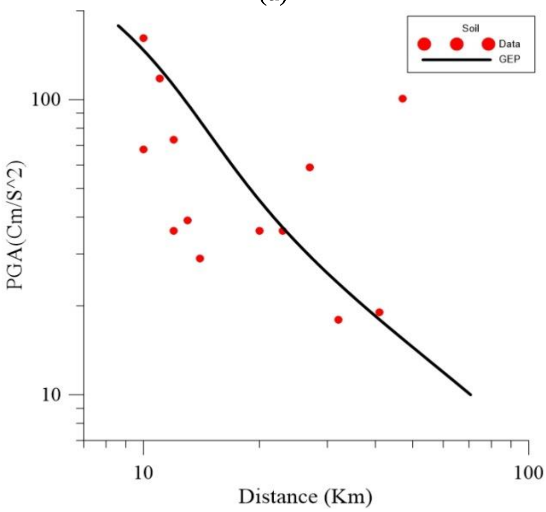
6. Conclusions

The ability of prediction ground motion parameters is one of the greatest appetencies of earthquake engineers. But since the researchers still did not arrive to that ideal point, some methods are used which can be useful to be close to the appetencies. This study aims to develop strong ground motion equations for the PGA in Alborz seismic zone in Iran using a novel application of GEP.

In this study 93 earthquake which recorded in Mazandaran province during the period 1975 and 2017, with moment magnitudes more than 4 and source to site distances between 6 kilometers to 178 kilometers had been gathered. Due to the shortage of the data, a regression technique had been used to create artificial data. In total,



(a)



(b)

Fig. 8 Distribution of data and varieties of the model for magnitude of 5 in site class of (a) rock, (b) soil

693 data sets had been contained to GEP approach by using this method. Two site conditions - soil and rock - have been considered in the analysis. The chosen shear wave velocity for separating these conditions was 375 $\frac{M}{S}$.

Not only is higher PGA quantities is anticipated in bigger earthquakes, but also new equations tend to more critical than other existed attenuation relationships in such earthquakes. However, in earthquakes with lower moment magnitudes it is apparent from the results that presented equations for soil and rock are roughly similar to other attenuation relationships.

The results of this study show that the equations earned by GEP approach have good R-square values (0.866 and 0.978 for soil and rock conditions respectively) and can be used in practical cases.

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