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The Development of a Local Ground Motion Prediction Equation from Recorded Data

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***Abstract* -** A representative attenuation relationship is one of the key components required in seismic hazard assessment of a region of interest. In this project, a ground-motion attenuation relationship for peak ground acceleration was developed for Sharjah, United Arab Emirates (UAE) region. Incorporated Research Institutions for Seismology (IRIS) as well as Building and Housing Research Center (BHRC) databases were utilized to collect strong ground motion of 90 horizontal component waveforms from different earthquakes measured by 440 stations in Iran and Sharjah. The collected dataset is composed from earthquakes that occurred in Iran with attenuation reaching UAE in moment magnitude varying from 4 to 7.3. The relationships derived are for distances up to 100 km, in a time period from 2008 to 2018. Attributes considered for each earthquake include earthquake date, time of occurrence, moment magnitude, depth, epicentral distance, acceleration time series, peak ground acceleration (PGA), and time shear velocity as well as event location and coordinates. A set of statistical analysis techniques was used to analyze and validate earthquake records. In this study, different attenuation relationship equations utilized for similar regions were collected from literature of previous work done in multiple countries. Based on the collected equations, new equations that are more suitable for Sharjah were developed by applying nonlinear regression analysis using Statistical Package for the Social Sciences (SPSS) statistics software and MATLAB. Accordingly, an optimum model was formulated that best suits Sharjah study area characteristics. The developed ground-motion prediction equations derived in the study can be used to predict earthquake-prone locations in UAE and other locations with similar characteristics. Additional artificial neural network (ANN) calculations were generated to verify the attenuated PGA mode in Sharjah based on Iranian attributes.

***Keywords*:** Attenuation equation, ground-motion prediction, nonlinear regression, ANN, United Arab Emirate.

1. Introduction

Seismic waveforms through earthquakes are affected significantly while propagating from the local site and spreading upward. Strong ground-motion parameters can vary according to conditions. One of the most essential strong ground-motion parameters is denoted by acceleration records verified for each earthquake. Peak ground-acceleration (PGA) information is critical for earthquake risk assessments and crisis response operations. Typically, earthquake hazard assessment is done by means of an earthquake ground-motion attenuation relationship or ground-motion prediction equation (GMPE). It provides the estimation of ground motion for an earthquake of a given magnitude at different distances through a curve fitted to observed data by the development of an attenuation relationship from recorded seismic events [1][2].

In order to estimate PGA, earthquake data were collected over the last decade. Many attenuation relationships were established using different statistical regression techniques by studying the association between acceleration values from several sources and site conditions. Collected records contain information about earthquake size, location to source distance, site conditions, earthquake depth, and faulting mechanism. Moreover, the time average shear-wave velocity (V_{S30}) is a frequently used parameter to represent the ground properties for seismic design. In this study, V_{S30} was used to examine soil characteristics of the stations [2][3]. Table 1 summarizes some of the earthquake GMPE developed in the last decade.

The structure of the presented research is outlined as follows. Data collected for earthquakes that occurred in Iran and attenuated to Sharjah will be presented. Different ground-motion prediction equations developed in previous research for similar regions will be discussed. Accordingly, the collected data of Iran will be passed through all the equations using nonlinear regression techniques (using SPSS programs) to obtain a response for Sharjah with data that are near the actual records at Sharjah recording stations. Furthermore, an artificial neural network (ANN) model to predict the PGA for Sharjah will be generated using the MATLAB machine learning toolbox. Lastly, a comparison between the developed models will be done, and suggestions and recommendations for future research will be discussed.

Table 1: Ground-motion prediction equations used in literature and their specifications.

Ref.	Epicenter location	Time Period	Calculated	No. of Records	Moment Magnitude (MW)	Depth R(km)
[1]	Turkey	1999 to 2006	PGA	402 records	> 4.0	4.9 -18.5
[2]	Iran	N/A	PGA, PSA for 5% of damping.	Simulated Records	5.0 - 7.5	5 - 200
[3]	Iran	1978 to 2008	PGA, PSA in terms of g	258 records from 109 Earthquakes Simulated Records	5.0 - 7.4	Up to 100
[4]	Malaysia	2004 to 2012	PGA in gals for subduction mechanism	130 total records from 7 earthquakes	/3.5	Up to 100
[5]	China	N/A	GMPE by heterogeneous Bayesian Learning	132 records from 29 stations	> 4.0	Up to 1000
[6]	USA	N/A	GMPE by using the ambient seismic field	Simulated Virtual Records	5.0 - 7.0	N/A
[7]	USA	N/A	(PGA, PGV & PSA at 0.3 and 1s)	188 Earthquakes simulated records	3.0 - 5.0	Up to 200
[8]	Italy	1972 to 2007	PGA, PGV and 5% damped PSA.	561 three-component waveforms from 107 earthquakes	4.0 - 6.9	Up to 100
[9]	N/A	N/A	GMPE developed for inelastic response spectra	Over 3,100 from 64 earthquakes	4.3 – 7.9	Up to 200
[10]	Italy	N/A	GMPEs for PGA, PGV, PSA	1213 recordings from 218 earthquakes	4.0 - 6.9	Up to 200
[11]	Indonesia	2000 to 2007	PGA, PGV & PSA	12 Earthquakes	5.0 – 9.0	200 – 1500
[12]	Bangladesh	1885 to 1999	Attenuation earthquake intensity equations	7 Earthquakes	5.1 - 8.1	up to 300
[13]	Turkey	1976 to 2004	PGA depending on rock site and soil site data	516 earthquakes	>= 4.0	Up to 200
[14]	Iran	N/A	Five regional earthquake prediction models	37 records from 35 earthquakes	4.0 – 7.0	Up to 150
[15]	Malaysia	2004 to 2012	PGA for earthquake	More than 150 records from 9 earthquakes	>= 3.5	N/A
[16]	Iran	1978 to 2012	GMPE for 5%-damped PSAGMPE	200 earthquakes	5.0 -7.4	Up to 100
[17]	Iran	Up to 2004	PGA, PGV, and EPA parameters	89 earthquake events including 307 earthquake records	4.5 - 7.5	Up to 150
[18]	Iran	1975 to 1995	PGH and PGV in three cases of site conditions	279 entries from about 30 areas	3.0 - 7.4	Up to 100

*** PGA: peak ground acceleration; PGV: peak ground velocity; GMPE: Ground-motion prediction equation; PSA: pseudo spectral acceleration for spectral periods; EPA: effective peak acceleration.**

2. Strong Motion Database

A total of 90 high ground-motion data in the study period of the last 10 years (from 2008 till 2018) were assessed as shown in Figure 1. The earthquake sources were Iran and each showed attenuation to United Arab Emirates (UAE). Iranian and UAE data were obtained from the Housing and Urban Development Research Centre (BHRC) and Incorporated Research Institutions for Seismology (IRIS) databases, respectively. With respect to the focal depth, shallow earthquakes with a threshold of 100 km were considered with moment magnitude of database ranges between 4.0 and 7.3.

Earthquake source information was collected by 31 different stations in Iran, while the corresponding attenuated signal was measured in University of Sharjah, Sharjah station (UOSS) with coordinates of 56.20° longitude and 24.95° latitude. Regression analyses were done for 90 time series records; 50 of these time series records occurred on rocks ($V_{S30} > 750$ m/s), 35 occurred on stiff soil ($360 < V_{S30} \leq 750$ m/s), and the rest ($180 < V_{S30} <= 360$ m/s) occurred on soft soil. Table 2 shows a sample of the collected data from Iran station with their characteristics with the corresponding peak ground horizontal acceleration (PGH) collected from Sharjah Station.

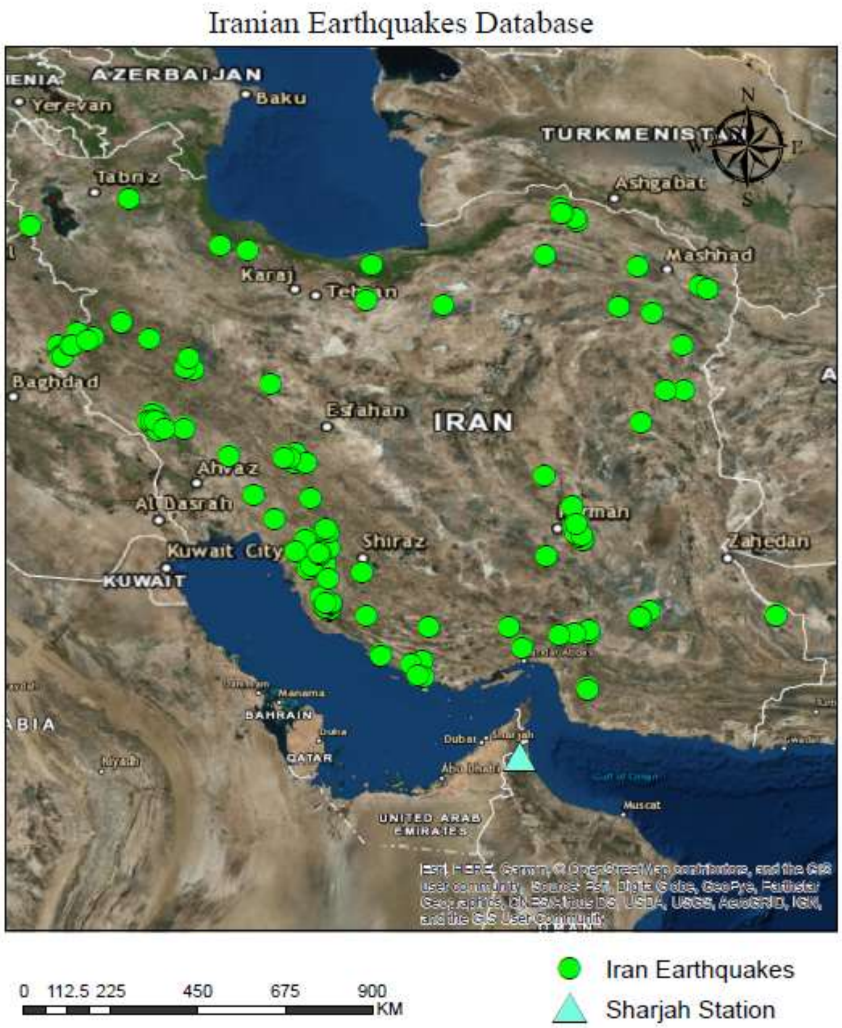


Fig. 1: Geographic distribution of the selected events and recording stations.

Table 2: Characteristics of selected records.

Date	Time		Lat.	Long.	Epicenter Distance (km)	Moment Magnitude (MW)	Depth (km)	Effective Duration L (s)	V_{S30} (m/s)	Actual PGH in Sharjah (UOSS)
5/26/2009	11:52:48	PM	33.94	48.6	19	4.6	22	2.17	891	0.442
10/13/2009	12:54:27	AM	35.05	46.93	70	5.1	10	14.15	514	0.526
2/23/2010	10:25:54	AM	32.57	48.38	16	5.4	16	5.46	582	0.691
7/20/2010	7:38:10	PM	27.16	53.92	49	5.9	18	15.13	567	13.105
7/30/2010	1:50:14	PM	35.28	59.26	52	5.9	20	21.29	1196	0.995
7/31/2010	6:52:59	AM	29.6	56.79	66	5.7	14	23.18	516	0.738
8/27/2010	7:23:48	PM	35.45	54.4	17	5.6	7	3.88	759	0.814
9/27/2010	11:22:46	AM	29.78	51.76	45	5.8	18	20.98	450	0.137
1/5/2011	5:55:47	AM	30.16	51.7	15	4.6	16	2.58	1262	0.703
1/5/2011	4:32:21	PM	30.18	51.66	15	4.5	16	2.94	1262	0.493
1/5/2011	5:50:53	PM	30.19	51.66	39	5	20	18.43	617	0.591
1/7/2011	11:52:59	PM	30.17	51.74	16	5.2	20	5.25	1262	0.522
6/15/2011	1:05:30	AM	27.8	57.79	11	4.9	16	3.77	776	4.032
6/26/2011	7:47:00	PM	30.03	57.58	31	5.2	22	12.97	604	3.870
7/26/2011	4:04:12	AM	36.61	56.76	18	4.9	18	18.16	155	4.020
1/11/2012	5:08:00	PM	36.38	52.74	39	5.2	16	17.86	514	3.089
2/5/2012	6:10:40	AM	28.66	51.56	23	5	18	11.62	853	3.540
3/18/2012	2:38:15	AM	36.83	49.22	17	5.5	10	4.76	898	2.806
5/3/2012	10:09:37	AM	32.88	47.72	10	4.8	12	2.46	1564	3.135
5/14/2012	10:12:35	AM	27.88	57.78	8	4.4	4	1.67	894	3.166
7/1/2012	2:49:46	AM	31.76	50.98	30	5.2	16	9.57	643	3.124
7/1/2012	10:01:26	PM	34.5	59.95	16	4.4	14	2.6	1477	0.004
7/24/2012	6:56:36	AM	31.77	50.93	18	4.9	16	4.14	919	4.230
9/2/2012	12:50:02	AM	33.44	59.99	20	5.4	18	4.51	1397	2.622
12/5/2012	5:08:11	PM	33.44	59.56	15	5.6	32	10.92	398	3.057

3. Development of Regional Attenuation Equation

The main purpose of this study was to derive a regional earthquake attenuation equation for Sharjah, UAE. Based on this objective, several equations were reviewed in recent literature with respect to locations with similar characteristics. The eight selected equations are discussed in Table 3.

Table 3: Selected equations as a basis for nonlinear regression analysis.

Ref.	Period	Mag.	Depth (km)	Location	Equation Used
[19]	1973 - 2004	4.5 to 7.5	Up to 30	UAE	$\mathrm{Log}_{10}(y) = C_1 + C_2 M + C_4 \mathrm{Log}_{10}(r) + C_A S_A + C_S S_S$
[20]	1902-2004	5.0 to 7.7	Up to 100	UAE	$\mathrm{LogPGA} = a + b(M-6) + c(M-6)^2 + kr + d \times \mathrm{Log}(r) + s$
[1]	1999 - 2006	Greater than 4.0	Up to 344	Turkey	$\mathrm{lnPGA} = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_v \ln \frac{V_{S30}}{V_{ref}}$
[2]	N/A	5.0, 6.0 and 7.0	Up to 100	Iran	$\mathrm{lnA(f)} = c_1(f) + c_2(f)M + c_3(f) \ln R + c_4(f)R + \varepsilon$
[21]	N/A	5.0 to 7.4	Up to 100	Iran	$\mathrm{Log}\, Y = a + b(M_w - 6) + c(M_w - 6)^2 + d\left(r_{jb}^2 + h^2\right)^{\frac{1}{2}} + \sigma$
[17]	1975 - 2004	4.5 to 7.5	5 to 150	Iran	$\ln y = C_1 + C_2 Ms + C_3 \ln[R + C_4 \exp[Ms]] + C_5 R$
[18]	N/A	3.0 to 7.4	Up to 100	Iran	$\mathrm{Ln}\,(A) = C_1 + C_2 \times (M-6) + C_3\, \mathrm{Ln}\,(\mathrm{sqrt}\,(EPD^2 + h^2))$
[22]	N/A	4.0 to 7.5	Up to 200	Europe	$\log(y) = C_1 + C_2 M + C_3 r + C_4 \log(r) + \sigma P$

4. Results and Discussion

4.1. Regression Results

In the present study, the summarized equations and their coefficients serve as a basis for regression analysis. The analysis of variance (ANOVA) technique used to distinguish between different regression results is shown in the following eight equations, using the same previously discussed variables:

$$\mathrm{Log}_{10}(y) = 0.115 + 0.206\, M + -0.430\, \mathrm{Log}_{10}(r) + 0.011\, S_A + 0.463\, S_S \tag{1}$$

$$\mathrm{LogPGA} = 1.17 + 0.670\,(M-6) + 0.325\,(M1-6)^2 + -0.011\, r + -0.036 \times \mathrm{Log}(r) \tag{2}$$

$$\mathrm{lnPGA} = 3.56 + 0.16\,(M-6) - 0.0052\,(M-6)^2 - 0.658 \ln r - 0.701 \ln \frac{V_{S30}}{V_{ref}} \tag{3}$$

$$\mathrm{lnA(f)} = 3.562\,(f) + 0.072(f)M - 0.914(f) \ln R + 0.0105\,(f)R + \varepsilon \tag{4}$$

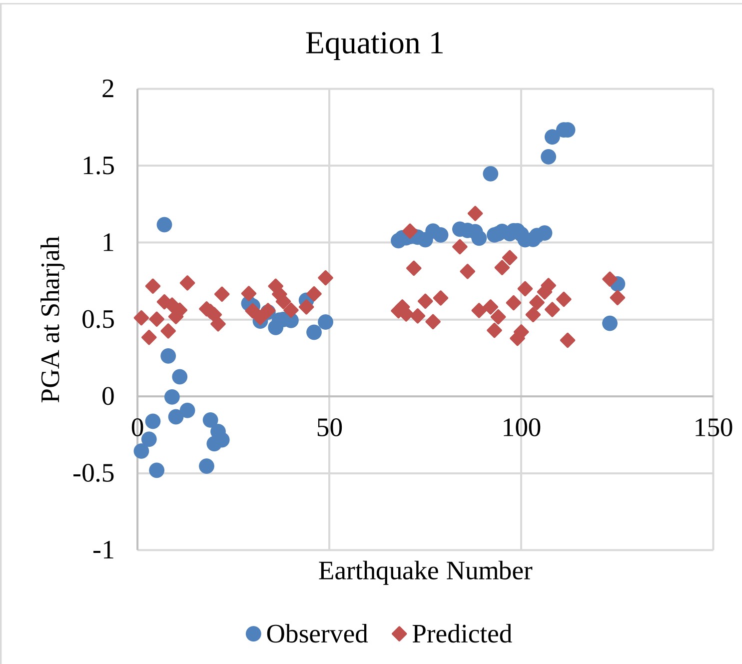
$$\mathrm{Log}\, Y = 1.198 + 0.704\,(M_w - 6) + 0.358\,(M_w - 6)^2 \pm 0.0115\,\left(r_{jb}^2 + h^2\right)^{\frac{1}{2}} + \sigma \tag{5}$$

$$\ln y = 1.209 + 0.17\, Ms + -0.275 \ln\left[R + -0.051 \exp[Ms]\right] + 0.002\, R \tag{6}$$

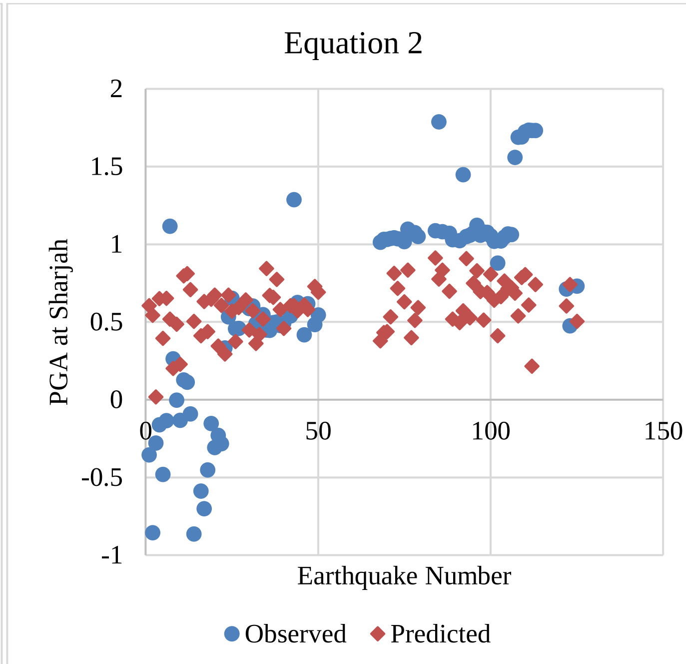
$$\mathrm{Ln}\,(A) = 3.678 + 0.2 \times (M-6) + -0.662\, \mathrm{Ln}\,(\mathrm{sqrt}\,(EPD^2 + h^2)) \tag{7}$$

$$\log(y) = 1.365 - 0.00254\, M + 0.002\, r - 0.638\, \log(r) + \sigma P \tag{8}$$

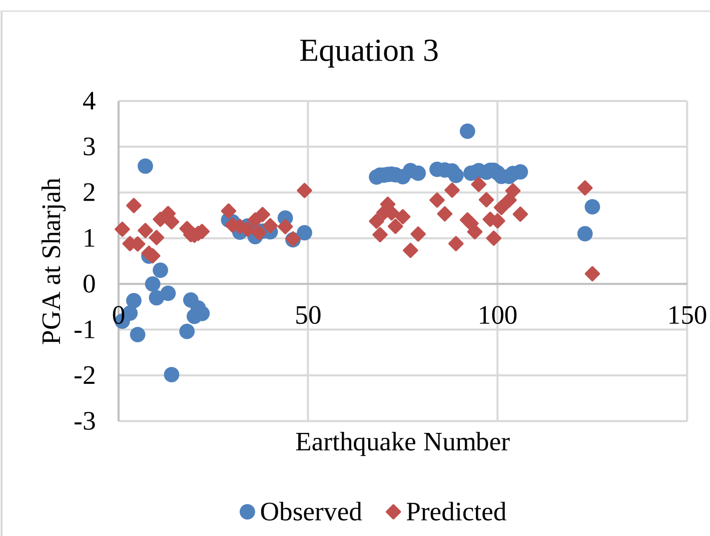
Statistical analysis was carried out on the modified equations, and equations confidence intervals have been obtained, considering Sharjah station accelerogram data as true values. Equation 3 showed the most accurate results, comparing to the true value in UOSS database, while the worst equation in prediction of peak ground accelerations was Equation 6. The difference in predictions refers to the different factor considerations and the type of computation in each equation compared to the others. Nonlinear regression results are illustrated in Figure 2.



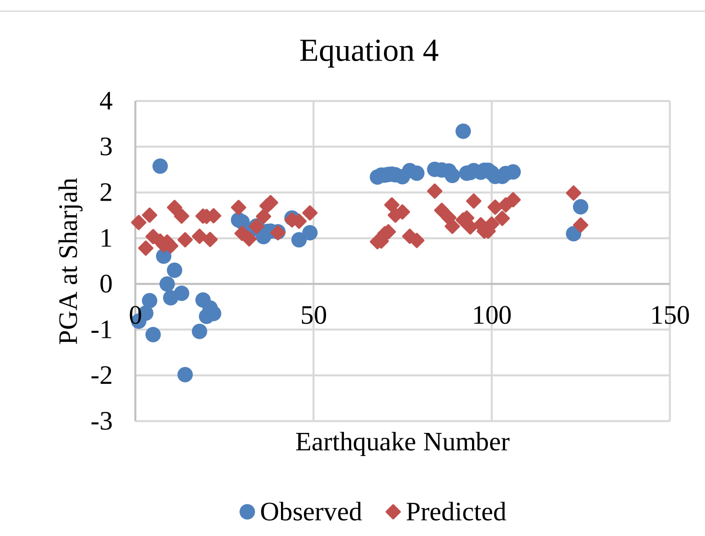
a) Modified equation 1 predicted PGA versus observed



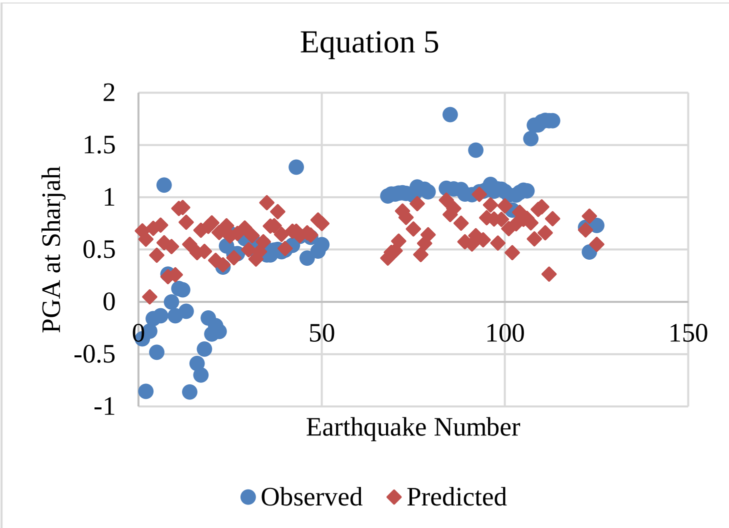
b) Modified equation 2 predicted PGA versus observed



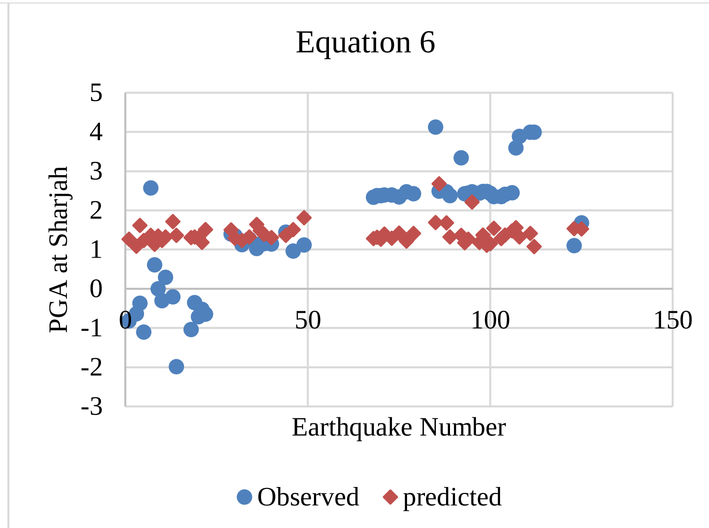
c) Modified equation 3 predicted PGA versus observed



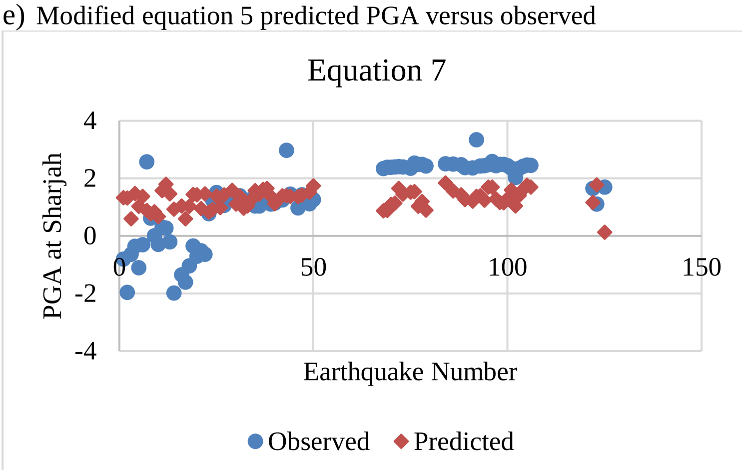
d) Modified equation 4 predicted PGA versus observed



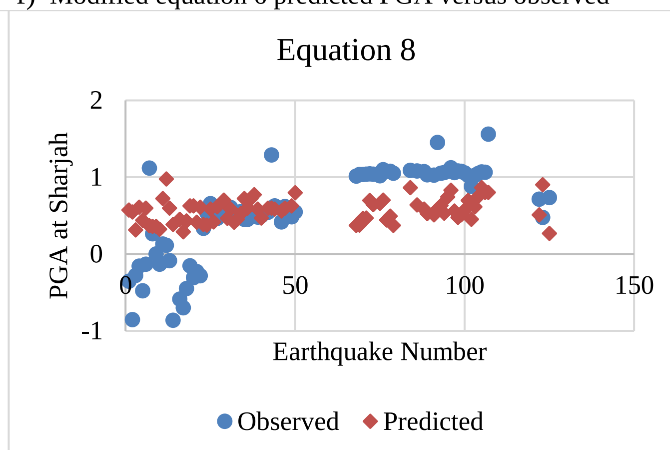
e) Modified equation 5 predicted PGA versus observed



f) Modified equation 6 predicted PGA versus observed



g) Modified equation 7 predicted PGA versus observed



h) Modified equation 8 predicted PGA versus observed

Fig. 2: Summary of the obtained results by the modified equations.

Accordingly, the obtained data were combined in one graph as shown in Figure 3, then used to formulate equation 9. Equation 9 is an optimal equation that can be utilized in predicting earthquakes at Sharjah, UAE, based on multiple factors and experience derived from literature and analysis. Figure 4 shows the results obtained by using equation 9.

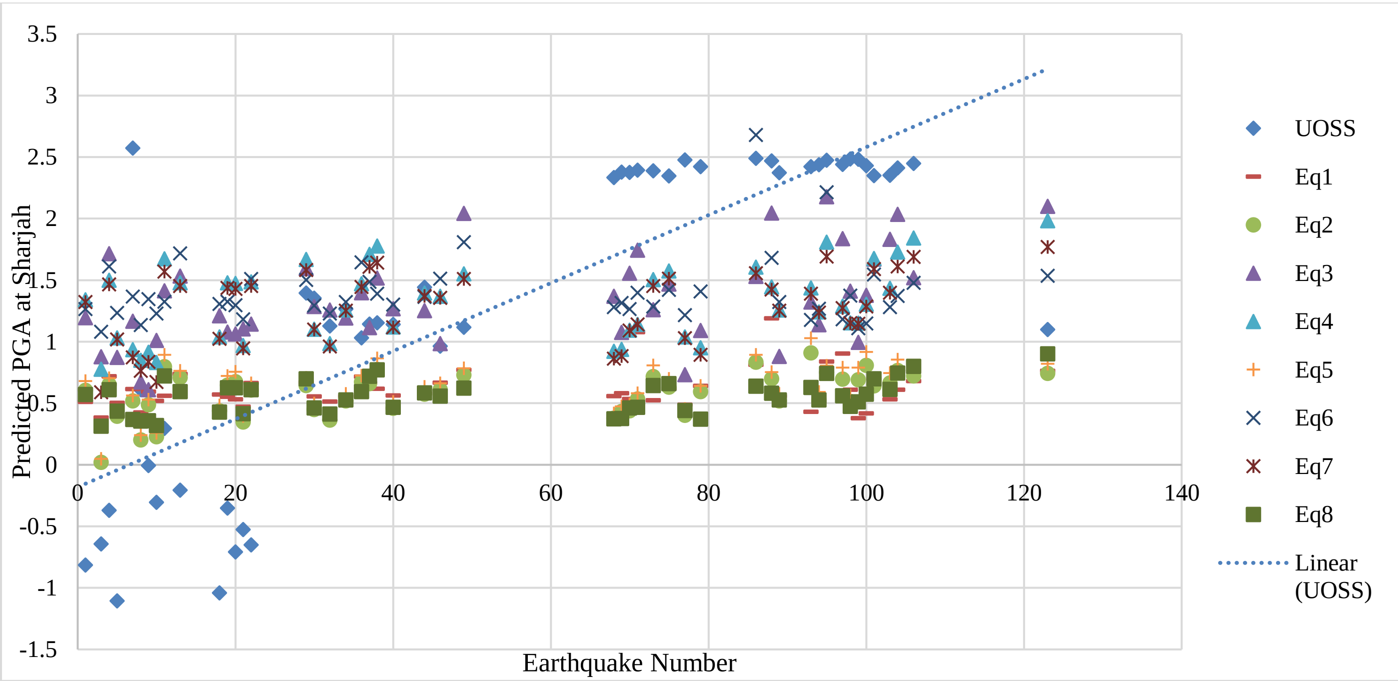


Fig. 3: Final modeled equation results.

Final formulated equation

$$\ln PGA = 0.262 + 2.681 \times (M_W - 6) + 1.247 \times (M_W - 6)^2 + 2.88 \times \log r + 0.069 \times r - 0.93 \times \ln \frac{V_{S30}}{V_{ref}} \tag{9}$$

Where, M_W is the moment magnitude; r is the hypocenter distance from earthquake position to the earthquake location; V_{S30} is the time-averaged shear wave velocity in the top 30 m of the site; and V_{ref} is a reference velocity = 760 m/s corresponding to the National Earthquake Hazards Reduction Program (NEHRP).

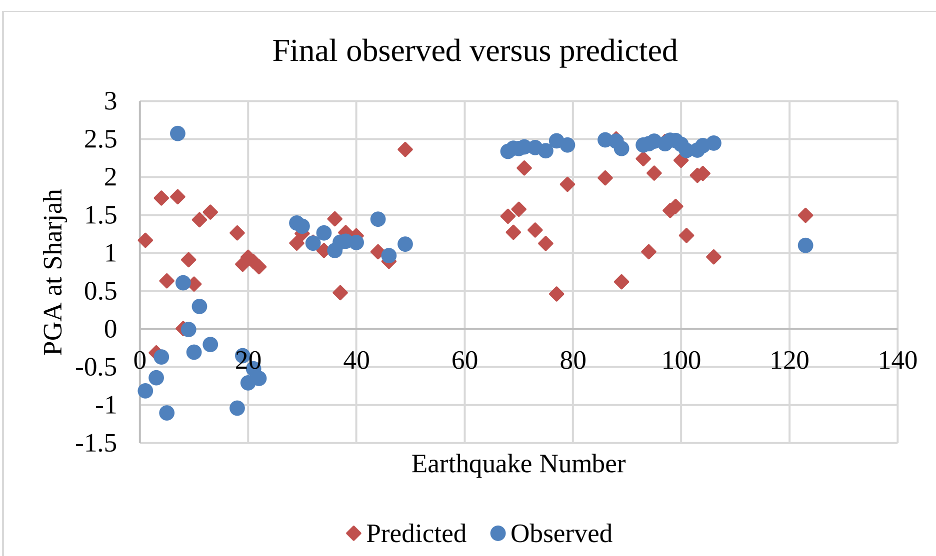
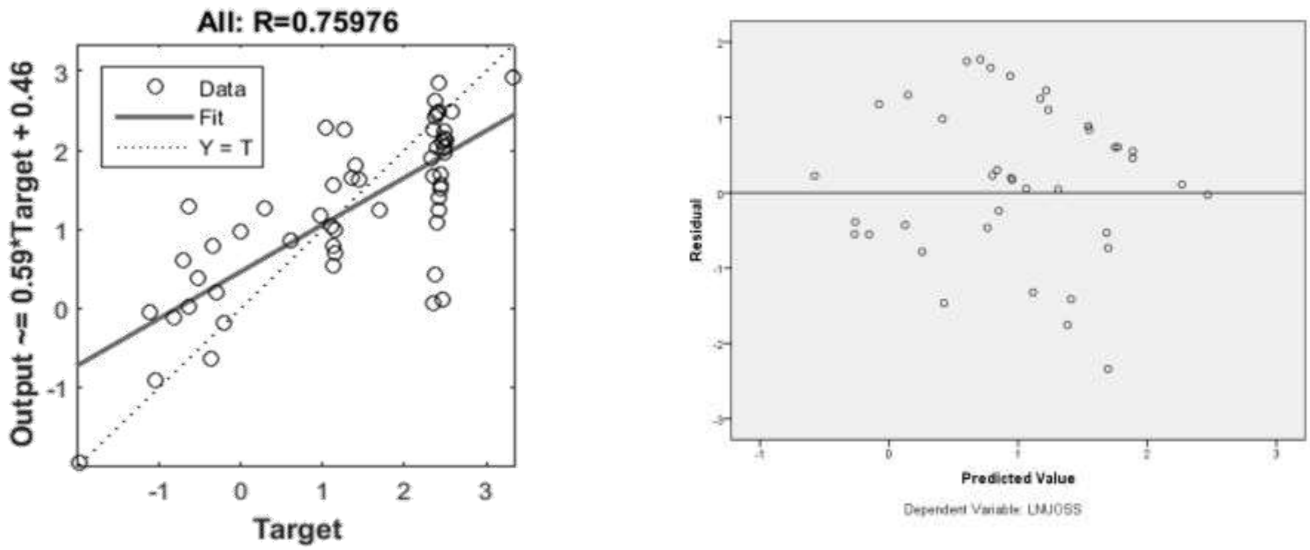


Fig. 4: Final modeled equation results.

4.2. Artificial Neural Network (ANN) Results

An artificial neural network was built to learn, model, and then validate findings. Figure 5 shows the ANN, which indicates high accuracy networking; the training and validation data have reached higher accuracy results than would have been obtained in normal regression methods. These results identify a more accurate result to be predicted. Such a network can be advanced to further learning by adding new obtained data.



a) ANN fitting performance from MATLAB

b) ANN fitting residuals using SPSS

Fig. 5: ANN model performance.

5. Conclusion

Simple descriptive statistical analyses were conducted to evaluate the collected earthquake data, and consequently minor modifications were made to improve prediction. Several peak ground-acceleration prediction equations were developed for the earthquakes attenuated to Sharjah in the UAE from large distances based on equations collected from the literature for locations with similar characteristics.

The developed equations were evaluated in terms of error sum of squares (SSE), mean squared error (MSE), and coefficient of determination (R^2) performance measures. Accordingly, a model was developed for predicting peak ground acceleration (PGA) for earthquakes that occur in Sharjah, UAE. The model took into consideration multiple parameters, namely: earthquake location, magnitude, depth, distance, and soil type. The developed model in this study is applicable for estimating PGA values for earthquakes where the following conditions apply: Moment magnitude: $4 \leq M_w \leq 7.3$, Hypocenter distance: $0 \leq R \leq 100$ km, and B, C, D, E soil classes (NEHRP).

The presented relationship was verified by an artificial neural network model for the purpose of predicting the PGA of earthquakes reaching the UAE as well as setting regulations and taking safety measures accordingly.

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