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STUDY ON RELATIONSHIPS BETWEEN MACROSEISMIC INTENSITY AND PEAK GROUND ACCELERATION, PEAK GROUND VELOCITY IN CHINA

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Abstract

This paper has collected the data of approximately 793 strong ground motion records, along with a comparable macroseismic intensity data from 28 China earthquakes, 52 America earthquakes, 9 Iran earthquakes and 8 Mexico earthquakes respectively, to develop relationships between macroseismic intensity (*I*) and peak ground acceleration (PGA), and peak ground velocity (PGV), by using weighted least squares method of set the weight of AHP and utilizing the boxplot to test the outlier of the data. Outlier test is used to ensure that raw data is a statistical real and effective. We then derived relationships between *I* and each ground-motion parameter by using a weighted least squares regression to fit a log-linear function, considering appropriate increase the weight in high intensity area and decrease the weight in low intensity area. The analysis results show that for peak acceleration with $\mathrm{V} \le I \le \mathrm{IX}$, $\log PGA = 0.268I + 0.330$, and for peak velocity with $\mathrm{V} \le I \le \mathrm{IX}$, $\log PGV = 0.277I - 0.753$. The statistic results indicate that PGA values of this paper is as about 1.3 times as that of the Chinese seismic intensity scale(CSIS2008) models with $\mathrm{V} \le I \le \mathrm{IX}$, meanwhile, PGV values of this paper is as about 1.24 times as CSIS2008 models with $\mathrm{V} \le I \le \mathrm{IX}$. Compared to the corresponding values in the ShakeMap system, the results of this paper are lower. It indicated that he CSIS2008 models, however, are conservative to earthquake hazard assessment and seismic design in China.

Key words: seismic intensity; PGA; PGV; earthquake hazard assessment

1. Introduction

Ever since recorded ground motion data became available, relationships between intensity scales and ground motion parameters have become a topic of intensive research. The reasons for this are simple. The corresponding relationship between them can get the intensity distribution in a very short period of time. Meanwhile, the intensity distribution can not only be used to quickly assess the earthquake disaster and loss, but also provide reference for the seismic design of the project. Studies have been conducted using regression techniques to develop empirical relationships between seismic intensity measure with peak ground motion parameters. Such as the relationship between seismic intensity and PGA (Hershberger, 1956; Ambraseys, 1974; Murphy and O'Brien, 1977; McMann, et al., 1980; Wald et al., 1999; Worden al., et al. 2012; Bilal and Askan, 2014), the relationship between seismic intensity and PGV (Panza et al., 1997; Wald et al., 1999; Wu et; al., 2003; Kaka and Atkinson, 2004; Atkinson and Kaka, 2007; Saman et al.,2011; Bilal and Askan, 2014), the relationship between seismic intensity and duration of strong ground motion (Trifunac and Westermo, 1977), the relationship between seismic intensity and response spectrum (Kaka and Atkinson, 2004), the relationship between intensity and cumulative absolute velocity(Cabanas et al, 1997; Kostov, 2005), the relationship between seismic intensity and fourier acceleration spectra (Sokolov and Chernov, 1998, Sokolov, 2002) and so on .These studies were based on data collected in different confined regions which could be distinguished by their local features. However, in the relationships between seismic intensity and ground motion, PGA and PGV values are regarded as the most direct, convenient and effective parameters to assessing intensity in these parameters, and the relationships between intensity and PGA, PGV are used in the ShakeMap system of USGS. so this paper proposes relationships between seismic intensity and PGA, PGV.

The PGA and PGV are taken as reference index to assess intensity in current CSIS2008. CSIS2008 is short for "The Chinese seismic intensity scale(GB/T 17742-2008)". But in the past 30 years, the PGA and PGV values are in perfect accordance with that of the Chinese seismic intensity scale(GB/T 17742-1980). However, the empirical relationships between seismic damage investigation and strong ground motions parameters indicates that there are partly differences between the two predict intensity. So the goal of the paper is to derive a relationship that can be used to estimate seismic intensity rapidly given instrumental recordings of ground motions. Relationships have been derived from intensity values that have been identifies from 97 earthquakes in the domestic and abroad at locations where strong motion instrumental records are also available.

2. Instrumental and Intensity Database

This paper has developed regression relationships between seismic intensity and peak ground acceleration and peak ground velocity. Therefore, we collect intensity values that have been identifies from the isoseismal maps at locations where strong motion instrumental records are also available. In order to guarantee the validity of seismic data of the collected, macroscopic intensity and strong motion instrumental records should be verifiable. Different countries use different intensity scales, and these can be very different. But some countries use same intensity levels, such as MMI and CSIS2008, both are 12 intensity levels. So this paper selects to the data that use the same intensity levels to assess intensity. The dataset of recorded accelerograms employed in this study comprises 793 horizontal records from 28 China earthquakes, 52 America earthquakes, 9 Iran earthquakes and 8 Mexico earthquakes respectively. The records in China have been installed by the China Strong Motion Networks Center(CSMN), that of America stems from "Strong Earthquake Accelerogram" published California Institute of Technology and National Oceanic and Atmospheric Administration (NOAA), that of Iran stems from Strong Motion Network Iran (ISMN) and the literature (Saman et al., 2011), and that of Mexico stem from the literature (Gama-Garcia and Gómez-Bernal, 2008). The recordings were taken from ground shaking which were of intensity levels ranging between Ⅴ and Ⅸ Geometric means of the two horizontal components of ground motions have been taken from all the records.

3. Outlier test

The core part of statistical analysis is to ensure that raw data is a general statistical property that is the real and effective. There will always be one or a few values deviate from obviously most of the data in the raw data. If there are such abnormal values, the error of the result of statistical analysis will increase. The statistical results may not be consistent with objective reality. Therefore, it is necessary to test the outlier of the data before the statistical analysis. This paper uses boxplot to test the outliers. The outlier is defined as the observation that the distance between the observed value and the bottom Q1 or top Q3 of the box is over 1.5 times more than height of box H (H=Q3-Q1). Figure 1 is boxplot of the dataset: (a) log*PGA* vs. Seismic Intensity; (b) log*PGV* vs. Seismic Intensity. Table 1 and 2 are respectively the mean of log*PGA* and log*PGV* for each intensity level after excluding outliers

Table 1 – Mean values of log*PGA* (cm/s/s)for each intensity level after excluding outliers

	China	No.	American	No.	Mexico	No.	Iran	No.	All	No.
Ⅴ	1.37	7	1.70	106	1.35	31	1.46	15	1.6	159
Ⅵ	1.91	114	2.03	167	1.65	33	1.84	15	1.93	334
Ⅶ	2.27	37	2.26	147	1.96	27	2.18	4	2.23	219
Ⅷ	2.55	17	2.66	29	2.19	10	--	--	2.50	60
Ⅸ	2.74	4	2.79	9	2.23	4	2.83	3	2.67	21

Table 2 – Mean values of log*PGV* (cm/s) for each intensity level after excluding outliers

	China	No.	American	No.	Mexico	No.	Iran	No.	All	No.
Ⅴ	0.8	2	0.75	105	0.41	31	0.59	9	0.66	147
Ⅵ	0.79	105	0.98	165	0.54	33	0.72	8	0.88	316
Ⅶ	1.06	34	1.34	149	0.86	28	1.30	2	1.22	215
Ⅷ	1.37	19	1.56	31	1.01	10	--	--	1.41	60
Ⅸ	1.73	4	1.91	9	1.44	5	2.01	1	1.75	19

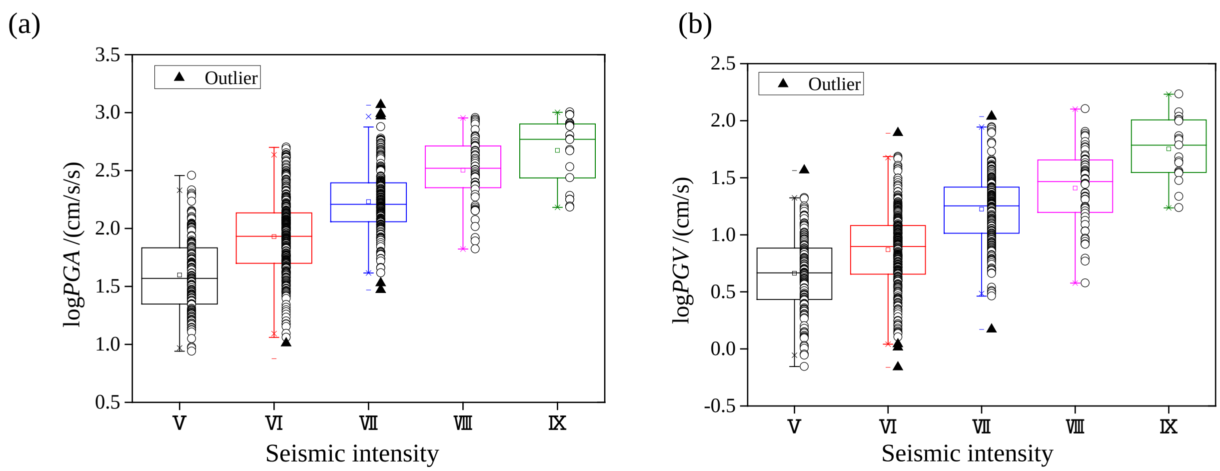

Fig. 1 – Boxplot e of the dataset: (a) log*PGA* vs. Seismic Intensity; (b) log*PGV* vs. Seismic Intensity.

4. Correlation analysis of seismic intensity and PGA and PGV

4.1 Data fitting method

The number of strong motion instrumental records is different in each intensity region. Such as the number in Ⅵdegree of the PGA of China data is 114, Ⅸdegree four record number, X degree only one record number that not listed in the Table 1. The data are not suitable for using ordinary least squares to fit prediction equation, so this paper will use the weighted least squares method to fit equation. The experience of intensity assessment shows that intensity assess of high intensity areas is relatively closer to the actual situation than that of low intensity regions in the estimation of seismic intensity in China. Therefore, we should be appropriate to increase the weight of high intensity area, and decrease the weight of low intensity area. Considering the above situation, we use analytic hierarchy process (AHP)(Chang and Jiang, 2007) to set weight. The method can solve multi-objective and complex question, and it is decision analysis method of qualitative and quantitative. Constructing judgment matrix is the most important part in this method. According to the expert experience of the seismic intensity assess, the order of importance of different intensity area should be followed: Ⅴ,Ⅵ, Ⅶ, Ⅷ, Ⅸ. Accordance with the principle constructed judgment matrix are shown in Table 3. Through the standardization of column and the average of standard column to fix weight coefficients, we finally perform a consistency check using *CR* (see Eq.(1)) to judge the rationality of the results.

Table 3 – Matrix of intensity structure judgment

Intensity	Ⅴ	Ⅵ	Ⅶ	Ⅷ	Ⅸ
Ⅴ	1	0.33	0.20	0.14	0.11
Ⅵ	3	1	0.33	0.25	0.20
Ⅶ	5	3	1	0.33	0.25
Ⅷ	7	4	3	1	0.33
Ⅸ	9	5	4	3	1

$$CR = \frac{CI}{RI} \tag{1}$$

Which, *CR* is the random consistency ratio of the judgment matrix; *CI* is the general consistency index of the judgment matrix; *RI* is the average random consistency index of judgment matrix, and it can be obtained to look-up table.

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{2}$$

Here $\lambda_{\max}$ =5.234, *CI*= 0.059, *CR*=0.052<0.1, It shows that the weight coefficients in Table 4 pass up the consistency check.

Table 4 – Weights of weighted least square fitting in different intensity regions

Intensity	Ⅴ	Ⅵ	Ⅶ	Ⅷ	Ⅸ
Weight	0.0355	0.0785	0.1489	0.2638	0.4733

4.2 Fitting results

Intensity levels are divided into 12 integer level, and intensity levels ranging between Ⅴ and Ⅸ is studied in this paper. Because the intensity is the nominal variables, it can be only used as independent variables. PGA or PGV is real number of zero to infinite. As the ordinal variable, they can be either independent variable or dependent variable. By observing the distribution of the data, a simple predictive equation was then proposed for regressing intensity against the mean log*X* values as shown below:

$$\log X = a \times I + b \tag{3}$$

Here, *X* is different ground motion parameters, such as PGA or PGV; *a* and *b* are the fitting coefficient; *I* is seismic intensity level.

The regression coefficients based on Eq. (3) as listed in Table 5 are respectively for predicting intensity values from various instrumental ground motion parameters including PGA and PGV. As can be seen from the Table 5, the fitting coefficient (*a*) of predictive equation is very close in each partition, fitting coefficient (*a*) for Iran is larger. The partition choose the data which is less than half of the data of the literature(Saman et al.,2011), and there is not data in Ⅷ degree for Iran. These factors can result in the larger coefficient. But the fitting coefficients (*a*) in the literature (Saman et al.,2011) is close to all other partitions in the paper.

Table 5 – Coefficients of Eq. (3) to predict intensity from log*PGA* and log*PGV*

	I - PGA				*I - PGV*			
	a	*b*	σ	R^2	*a*	*b*	σ	R^2
China	0.302	0.107	0.093	0.57	0.3	-1.018	0.090	0.59
American	0.283	0.303	0.084	0.56	0.293	-0.739	0.086	0.57
Mexico	0.225	0.326	0.049	0.77	0.263	-0.998	0.095	0.58
Iran	0.33	-0.046	0.090	0.77	0.385	-1.473	0.090	0.79
All	0.268	0.330	0.099	0.49	0.277	-0.753	0.105	0.47

Figure 3 shows the proposed relationship between *I* and PGA, PGV for China, American, Mexico, Iran and All. As can be seen from the figure, fitting result for Mexico is the lower to that of other partitions. There has been more special soil structure under the ground in Mexico. It makes that the damage is more serious, and peak parameters of ground motion is lower in the earthquake. As can be seen from the Figure 3a, the fitting coefficients of predictive equation is close for America, China and the total data. As can be seen from the Figure 3b, regression line of all three are almost parallel, the predictive value from high to low as follow: American, All, China. As a whole, despite huge differences in constriction practices, architectural form and the seismotectonic settings between China and American, it is observed from Figure 3 that the model developed by regression analysis is generally consistent with well-established models developed previously. Although fitting coefficient of regression equation are differences, the change trend of the ground motion parameters in different areas as the intensity increases is similar.

(a) (b)

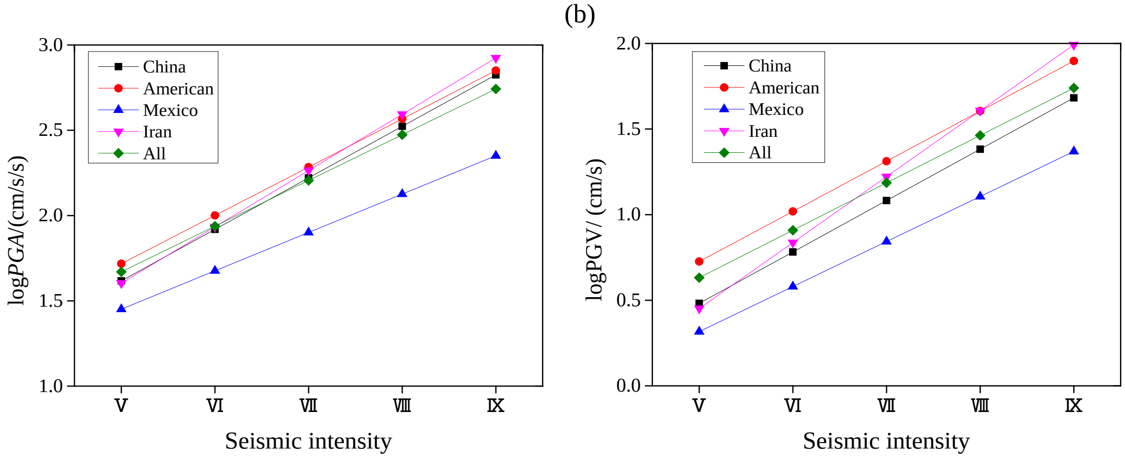

Figure 3 – Proposed relationship between intensity and log*PGA*、log*PGV*

4.3 Residual analysis

Residual analysis is difference analysis between the predicted intensity and the observed intensity. If the average residual is greater than zero, it is explained that the observed intensity is over estimated; Conversely, if the average residual is less than zero, the observed intensity is underestimated. Figure 4 shows the residuals data of the intensity predicted from PGA, PGV with respect to observed intensity, along with the average residual and the absolute average residual in each intensity. As can be seen From the Figure 4a, the observed intensity is underestimated in the Ⅴ and Ⅸ. The average residual is close to zero from Ⅵ to Ⅷ, it is explained that the observed intensity is close to the predicted intensity. The range of residual is gradually decreases with intensity increasing. As can be seen from the Figure 4b, the observed intensity is over estimated in the Ⅴ, Ⅶ and Ⅸ, but underestimated in the Ⅵ and Ⅷ. Residual analysis between Intensity and PGA, PGV showed that the absolute average residual is located at 1or so. The result is in good agreement with the characteristics that the intensity has fuzzy, average, comprehensive and subjective .

(a) (b)

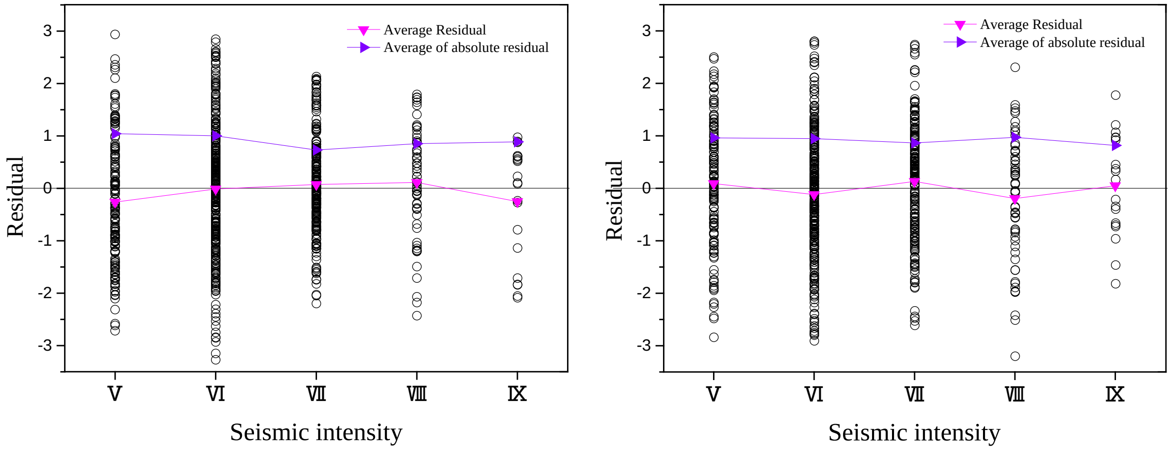

Figure 4 –Residuals of the intensity predicted from PGA, PGV with respect to observed intensity

This paper regards the results of the total data by regression analysis as the quantitative relationships between the intensity and PGA, PGV. So we find that for PGA in the limited range of Ⅴ≤I≤Ⅸ,

$$logPGA=0.268I+0.330 \qquad (4)$$

and for PGV within the range of Ⅴ≤I≤Ⅸ,

$$logPGV=0.277I-0.753 \qquad (5)$$

Table 6 gives the peak ground motion values and range that correspond to each unit intensity value according to our regression of the observed peak ground motions and intensities for domestic and international earthquake.

Table 6 –Values and ranges of ground motions for seismic intensities

Intensity	Ⅴ	Ⅵ	Ⅶ	Ⅷ	Ⅸ
PGA（cm/s/s）	47 [34-64)	87 [64-118)	161 [118-219)	298 [219-406)	552 [406-752)
PGV（cm/s）	4.3 [3.1-5.9)	8.1 [5.9-11.2)	15.3 [11.2-21.1)	29 [21.1-39.9)	55 [39.9-75.6)

4.4 Results comparison and discussion

PGA-I and *PGV-I* conversion relationships in the log-linear form(Eq.(3)) has been derived from linear regression of seismic data of different areas. Figure 5 presents correlations of intensity values with PGA and PGV values based on this study for comparison with correlations of the CSIS2008; Lin lin, 2011; Ma et al., 2014 and the result after 1980 year models. The related research results after 1980 year is the mean of the relationships of previous studies for PGA and PGV values to intensity values in 1981-2014(Ding et al. 2014).

As can be seen from the Figure 5, PGA and PGV values of the Ma et al.,2014 model along with the rising of Intensity is greater than that of other models. In Figure 5a, the slope of the predictive equation developed in this study is close to that of the CSIS2008 model, the result after 1980 year models and Lin lin, 2011model. for a given PGA values. Lower intensity values could be predicted using the conversion relationship of Lin lin, 2011 while higher intensity values using the conversion relationship of CSIS2008. PGA values of this paper is as about 1.23 times as that of the result after 1980 year in Ⅴ-Ⅶdegree while close to models of the result after 1980 year in Ⅷand Ⅸdegree. PGA values of this paper is as about 1.3 times as CSIS2008 models. In Figure 5b, PGV values of this paper is as about 1.24 times as CSIS2008 models, PGV values of Lin lin, 2011 model is as about 1.18 times as that of this paper.

(a) (b)

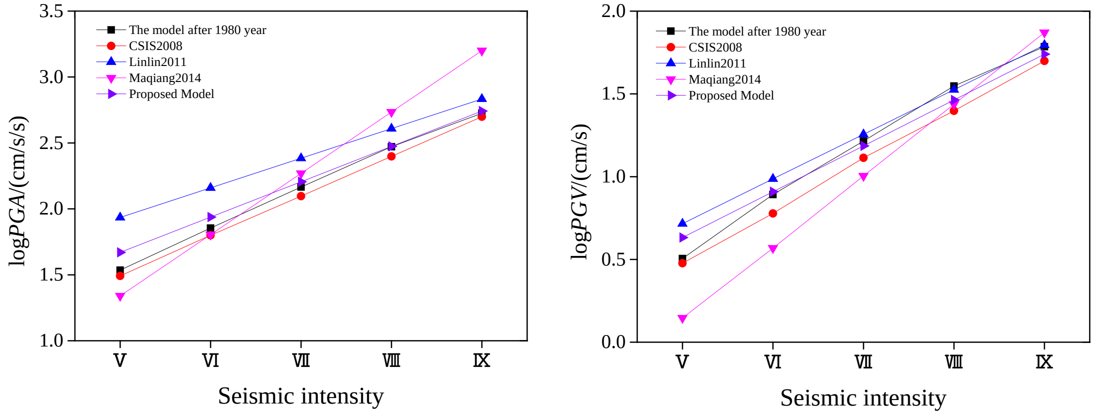

Figure 5 – Comparison of the results of the regression and the relevant research results in China

Figure 6 presents correlations of intensity values with PGA and PGV values based on this study of all and the American data for comparison with correlations of Trifunac and Brady,1975; Wald et al.1999; Worden et al. 2012; Faenza and Michelini,2010; Saman et al.,2011 and Bilal and Askan,2014 models. PGA and PGV values of Trifunac and Brady1975 is close to that of CSIS2008 models. As can be seen from the Figure 6. PGA and PGV values of this paper is greater than that of Faenza and Michelini2010, Saman et al. 2011 and Bilal and Askan2014, while less than that of Wald et al.1999, Worden et al. 2012 and the American data. In Figure 6a, PGA values of this paper is about 84% of that of the model of American data. PGA values of the model of American data is as about 1.8 times as Trifunac and Brady1975, about 1.1 times as Worden et al. 2012 and about 90% of that of Wald et al.1999. In Figure 6b, PGV values of this paper is about 75% of that of the model of American data. PGV values of the model of American data is as about 1.8 times as Trifunac and Brady1975, about 1.2 times as Worden et al. 2012 and very close to that of Wald et al.1999.

(a) (b)

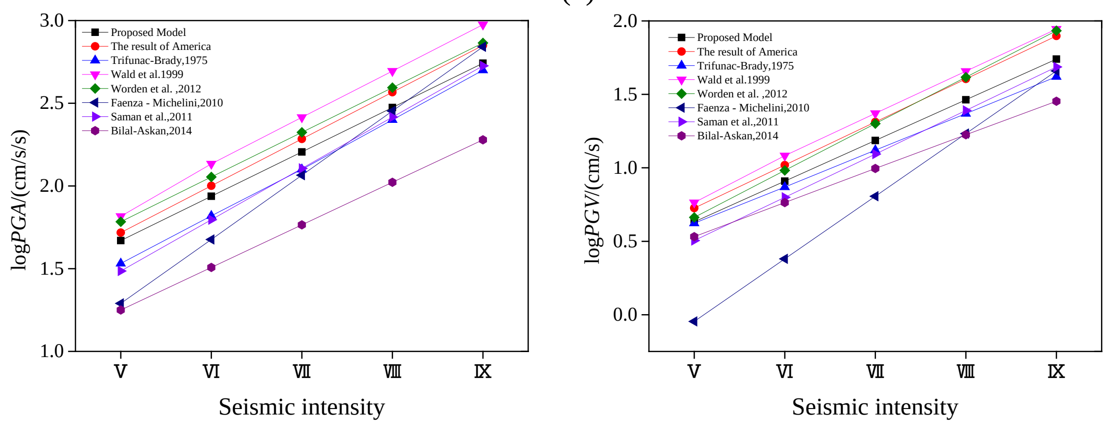

Figure 6 – Comparison of the results of the regression and other studies

5. Conclusion

This paper was aimed at studying correlations between ground motion parameters that calculated from instrumental strong motion records and observed intensity values in 97 earthquakes at home and abroad.

The results of statistical analysis show that PGA and PGV values of current Intensity scale is lower. Developed new regression relationships between the intensity and PGA, PGV. (the details of which have been summarized in Eq.(4) , (5) and Table 6). The Intensity values predicted by the relationships are higher than that of CSIS 2008. New regression relationship can be used for intensity rapid assessment, emergency response, loss estimation and for public information through the media.

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