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A Test of the Applicability of NGA Models to the Strong Ground-Motion Data in the Iranian Plateau

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The Next Generation Attenuation (NGA) project has now published several new sets of empirical ground-motion prediction equations (GMPEs) for PGA, PGV, and response spectral ordinates. These models significantly advance the state-of-the-art empirical ground-motion modeling and account for many effects that have not been directly accounted for in the existing Iranian GMPEs. Assuming that the present strong-motion database in Iran is unlikely to drastically change in the near future, the question we ask in this study is: Can the NGA models be applied in Iran? In order to answer this question, the NGA models of Boore and Atkinson [2008], Campbell and Bozorgnia, [2008], and Chiou and Youngs [2008], which are shown to be representative of all NGA models, are compared with the Iranian strong-motion database. The database used in this study comprises 863 two-component horizontal acceleration time series recorded within 100 km of epicentral distances for 166 earthquakes in Iran with magnitudes ranging from 4.0–7.4. The comparisons are made using analyses of residuals. The analysis indicates that the NGA models may confidently be applied within the Iranian plateau. To provide more reliable constraint on finite-fault effects and nonlinear site response in the Iranian equations, it would be useful to drive new GMPEs based on a merger of the NGA and Iranian databases.

Keywords NGA; Iran; Strong–motion; Sites; Faults; Earthquakes

1. Introduction

The area under the present study extends from 25–40° north latitude and 44–62° east longitude (Fig. 1). It is a region of conspicuous series of fold ranges formed during the Alpine earth-movements of the Tertiary Period. The Hindu Kush Mountains continue westward along the northern rim of the Iranian Plateau, passing into the Alburz Mountains of northern Iran. Culminating in the extinct volcano of Damavand, 18,700 ft, the Alborz Mountains run in an east-west direction, along the southern shores of the Caspian Sea, and continue to the northwest into the Armenian Knot, where the borders of Iran, Turkey, and Armenia meet. Another system of mountain ranges, consisting of the Zagros Mountains—which overlook the Tigris Valley, the Persian Gulf, and the Gulf of Oman—and of the Sulaiman Mountains of West Pakistan—which overlook the Indus Valley—connects the Armenian and Pamir knots to circumvent the Iranian Plateau. Along the western borders of Iran and before they bend eastward, the Zagros Mountains form a series of parallel hog's back ridges which rise to elevations over 14,000 ft. In the

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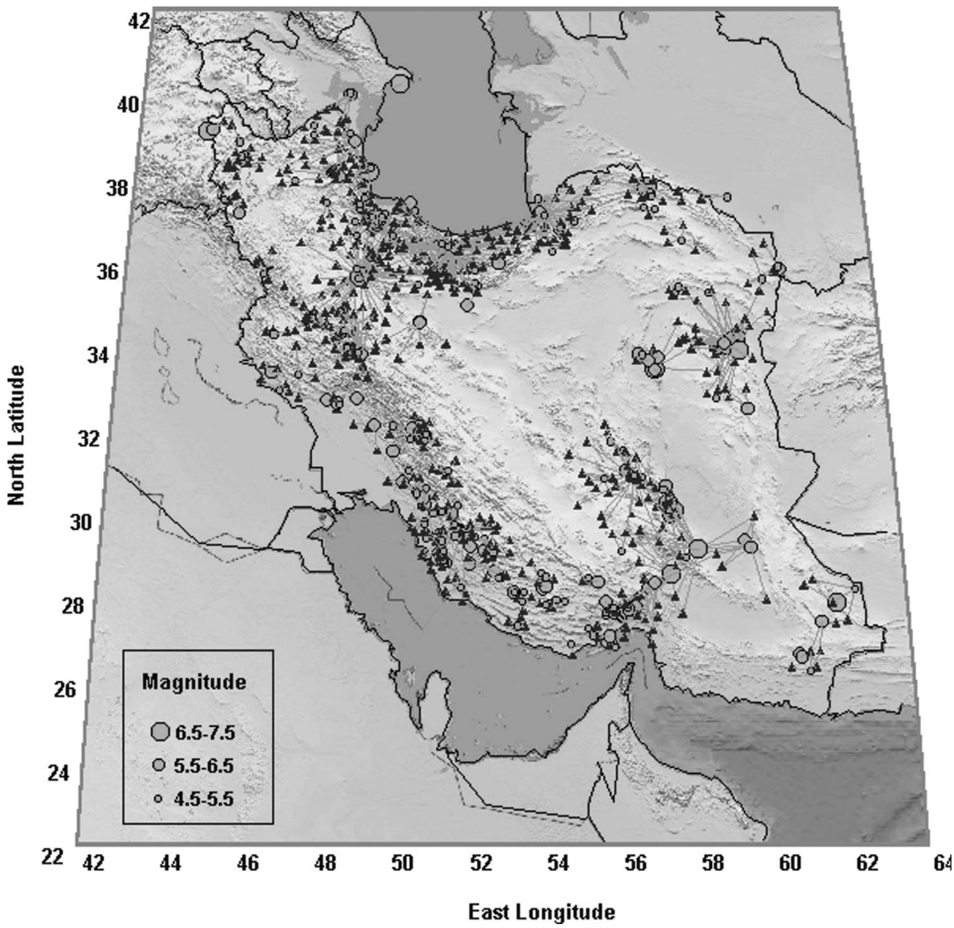

FIGURE 1 Earthquake locations and their corresponding recording stations.

central region lies the highlands of the Iranian Plateau, about 3,000–5,000 ft in height, which consist of horizontal or slightly folded sandstones, limestones, and chalks of predominately Tertiary and Cretaceous age [Clapp, 1940].

The tectonics and seismicity of the whole area or parts of it has been previously studied by several investigators [Niazi and Basford, 1968; Nowroozi, 1971; Takin, 1972; Stocklin, 1974, 1977; Seyed-Nabavi, 1977, 1979; Shoja-Taheri and Niazi, 1981; and Ambraseys and Melville, 1982). Iran, as a region with high level of seismic activity, has been experiencing numerous catastrophic earthquakes throughout its long history [Stahl, 1911, 1962; Wilson, 1930; Ambraseys and Melville, 1982]. In their seismicity analysis of the earth, Gutenberg and Richter [1954] estimated the seismic energy released by Baluchistan and Iran earthquakes to account for 2.7% of the total energy of all shallow earthquakes. Among 42 regions listed, only 13 contributed more. Instrumental seismicity in Iran shows that among the main seismic zones in Iran Zagros is considerably more active than in Alborz and Eastern zones. The release of moment rate in this zone is about five times larger than those in Alborz and Eastern zones. Although the annual number of events in Zagros is larger than those in other mobile zones, but the upper bond of its magnitudes is generally less than Alborz and Eastern Iran and is not larger than about 7.0 [Shoja-Taheri and Niazi, 1981].

Studies concerned with the evaluation of seismic hazards related to ground shaking make a significant use of predictive models that are referred to as attenuation relations. Such models are generally expressed as mathematical functions relating a strong motion parameter to parameters characterizing the earthquake source, propagation medium, and local site geology. Peak ground motions are the strong motion parameters generally used by engineers to seismic loads and intensity of shaking. There have been several studies on attenuation of seismic waves in the Iranian plateau using the Iranian strong-motion dataset (e.g., Khademi [2002]; Zaré and Sabzali [2006]; Shoja-Taheri [2002]; Shoja-Taheri *et al*. [2007]; Meghdadi [2008]). Shoja-Taheri [2002] developed attenuation relations employing two-step procedure for horizontal peak ground acceleration (PGA), horizontal peak ground velocity (PGV), and 5%-damped pseudo-absolute-acceleration spectra (PSA) at periods of 0.2 and 0.3 s for the main seismic zones of the Iranian plateau (Alborz, Zagros, and Eastern Iran). To evaluate M_L scale in Iran and in its sub-regions, Shoja-Taheri *et al*. [2007] indicated that the distance correction curves show tri-linear behavior for geometrical spreading. Meghdadi [2008], in her recent study of frequency-dependent parameters of the strong-motion data in Khorasan Province of Iran, also concluded that the distance corrections of the geometrical spreading follow tri-linear trends for different frequency bands. Due to the lack of sufficient information on the site conditions of the recording stations and also the fault type of the earthquakes, in all the studies referenced above the resulting GMPEs were derived for any particular seismic zones in this country without making differentiation between the event fault type or site soil specifications. Employing of such GMPEs in a seismic risk analysis may reduce the certainty of an unbiased estimation of the results. With more precise information which is now becoming available on both mechanism of the recorded earthquakes and sit soil specification of the recording sites in Iran and also the availability of a large amount of the strong motion data recorded by the National Strong Motion Network of Iran (NSMNI; http://www.bhrc.ac.ir) since its inception in 1973, has provided us the opportunity to test the applicability of the NGA models to the strong ground motion dataset in the Iranian Plateau.

The the Next Generation Attenuation (NGA) project (http://peer.Berkeley.edu/products/nga_project.html) has resulted in the publication of five new ground-motion models to predict PGA, PGV, and response spectral ordinates for periods up to 10 s [Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008; Idriss, 2008]. These models include new features accounting for effects such the influence of the nonlinear site, sediment depth and hanging walls. Hereafter, we respectively abbreviate Boore and Atkinson, Campbell and Bozorgnia, and Chiou and Youngs by BA, CB, and CY for convenience.

The purpose of the NGA project was to develop empirical equations to predict main shock ground-motions in shallow crustal earthquakes in active tectonic regions. These new equations might also be applied as ground-motion prediction in other parts of the world with the similar tectonic environment, such as the region encompassing the Iranian plateau. The purpose of this article is to test the applicability of the NGA equations to Iran’s strong-motion dataset for a particular measure of horizontal-component ground motions as a function of earthquake magnitude, source-to-site distance, local average shear-wave velocity in soil, and fault mechanism (i.e., normal, strike-slip, and reverse).

To perform this test we have arbitrary chosen only three out sets of the NGA equations developed by the NGA project groups [Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008] as representative of all the NGA models. The models are used for PGA, PGV, and 5%-damped PSA at periods between 0.01 and 10 s, all for the horizontal component. In this study, similar to NGA project, the measurements of the response variables are not the geometric mean of the two recorded horizontal components, but GMRoti50 as proposed by Boore *et al*. [2006]. So, this measure is independent of the original sensor orientations and is based on a set of geometric means computed from the as-recorded orthogonal horizontal motions rotated through all possible non redundant rotation angles.

2. Distribution of Data by *M*, Source Distance *R*, Fault type, and Site Class

At the early stage of this study we intended to include all the available data extended up to 200 km of source distances, but the resulted large residuals at far distances convinced us to limit our analyses only to the dataset within 100 km from the epicenters.

The dataset used in this study consists of 863 horizontal strong–motion time series recorded in Iran in 166 crustal earthquakes in the epicentral distance range from 0–100 km with magnitudes between 4.0 and 7.4 occurred between 1973 and 2006. To make sure that the reported locations of the events have sufficient accuracy for this study we relocated all the events using the strong-motion dataset. The relocation process showed considerable improvement on both the epicenters and particularly on the reported depths of the events. We found that in many cases the revised depths were much less than the 33 km which are generally assigned and reported by international agencies. There have been numerous cases, in different seismic zones in Iran, particularly in Zagros where the revised depths were found to be shallow (e.g., about 5 Km), while the reported depths were even much more then 33 km.

We selected those earthquakes which were recorded by at least three stations. Figure 1 shows the earthquake locations and the corresponding recording stations. Table 1 lists the number of events and recordings in different magnitude range. We employed HARVARD reported M_W in this study. But for those earthquakes with magnitudes less than 5.0, and for those earthquakes which occurred prior to 1976, we estimated their moment magnitude, $M_{W,}$ from the strong motion records. For the source distance, we used R_{rup} (closest distance to the fault) for the events associated with observable surface ruptures. For other events we used their hypocentral distances when R_{rup} were not available. Figure 2 shows distribution of magnitude versus distance, with different symbols representing different fault types. As shown in this figure, fault types of most of the smaller earthquakes are not known. Table 2 lists the number of earthquakes and recordings for different fault types. Table 3 lists the number of events and the available recordings at each period. The distribution of magnitude versus distance, for different site classes (based on NEHRP site classification) is shown in Fig. 3. Table 4 list the number of recordings for each site class. Soil types of the stations were evaluated by using either seismic refraction method, or by the available geological maps. As shown in Table 4, about 55% of the recordings correspond to the stations where no information on their site conditions is available. Field inspection of the stations with unknown site condition, however, shows that the site of these stations can presumably be assigned as either C or D class. In order to include recordings of the unknown sites in our analysis, we assigned class C for these stations based on trial and error evaluation of the residuals. Table 5 lists the number of events versus the number of recorded stations.

TABLE 1 Number of events and recordings in different magnitude range

M_W	4.0–4.4	4.5–4.9	5.0–5.4	5.5–5.9	6.0–6.4	6.5–6.9	7.0–7.5
No. of Events	40	55	35	17	10	5	4
No. of Records	139	245	202	85	148	24	20
Distance (km)	1.5–52	3–94	6–98	0.2–97	11–100	1–100	3–99

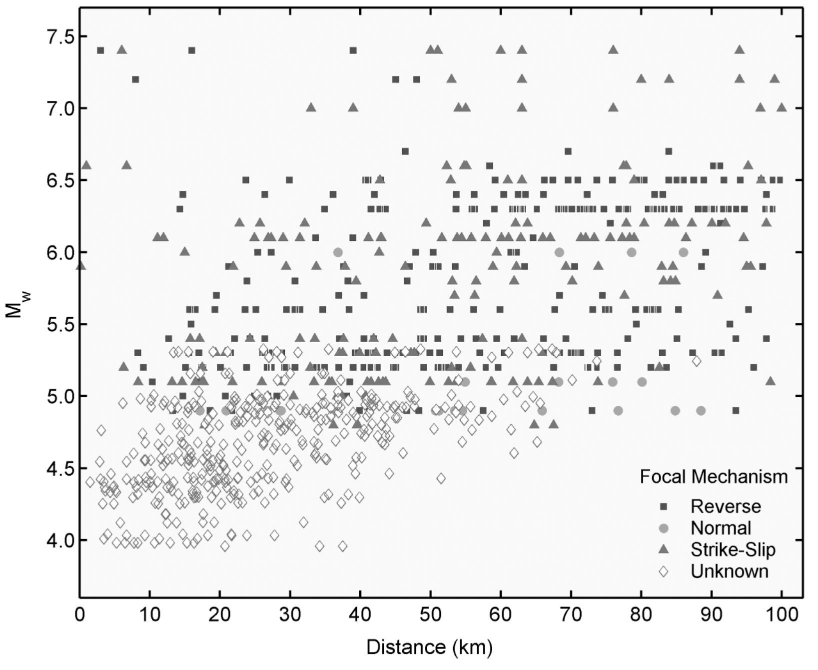

FIGURE 2 Distribution of the magnitudes vs. distance. The symbols represent different fault types.

TABLE 2 Number of events and recordings in different fault types

	Unknown	Reverse	Normal	Strike-Slip
Number of Events	95	41	3	27
Number of Records	378	289	22	174

TABLE 3 Number of events versus the number of available recordings at each period

Period (s)	0.02	0.03	0.05	0.075	0.10	0.15	0.20	0.25	0.30	0.40
No. of Events	166	166	166	166	166	166	166	166	166	166
No. of Records	863	863	863	863	863	863	863	862	862	862
Period (s)	0.50	0.75	1.0	1.5	2.0	3.0	4.0	5.0	7.5	10.0
No. of Events	166	160	153	133	132	111	88	76	48	29
No. of Records	861	840	813	725	722	619	520	452	319	214

TABLE 4 Number of recordings for each site class

Site class (NEHRP)	A	B	C	D	E	Unknown
Number of records	0	60	104	127	47	525

TABLE 5 Number of events vs. number of recording stations

Number of events	72	33	21	9	10	7	3	11
Number of stations	3	4	5	6	7	8	9	≥10

To evaluate the extent of applicability of the NGA equations to the Iran's strong motion dataset, we applied each of the selected NGA equations separately to the Iran's dataset, and calculated the *Residuals* and their corresponding *RMS* values. Residuals shown by Eq. (1) are generally defined as the differences between the natural logarithm of the observed and calculated strong motion variable parameters:

$$r_{ij} = \ln Y_{ij} - \ln \hat{Y}. \quad (1)$$

Here, $\ln Y_{ij}$ is the value of the *j*-th records of the *i*-th event, and $\ln \hat{Y}$ is the mean value of $\ln Y$. If the mean of residuals for the *i*-th event with N_i records is defined as:

$$\eta_i = \frac{1}{N_i} \sum_{j=1}^{N_i} r_{ij}. \quad (2)$$

Then the *intra-event* and *inter-event* residuals are defined, respectively, as:

$$r_{ij}^{(intra)} = r_{ij} - \eta_i \quad (3)$$

$$r_i^{(inter)} = \eta_i - \frac{1}{N_e} \sum_{i=1}^{N_e} \eta_i, \quad (4)$$

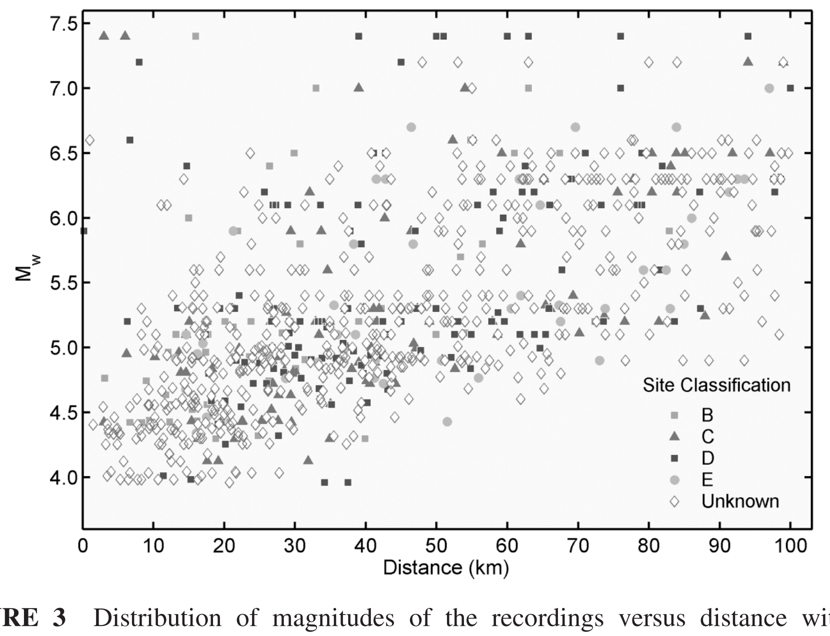

FIGURE 3 Distribution of magnitudes of the recordings versus distance with the symbols representing different site classes based on NEHRP site classification.

where N_e is the total number of events. Since both *intra-event* and *inter-event* residuals tend to be very close to zero, they will, therefore, represent respectively the residuals related to each individual source and to combined source*s*. In the following, we discuss the results of the residuals by considering the related figures.

Figure 4 illustrates the residuals and intra-event residuals (using Eqs. (1) and (3)) vs. distance and inter-event residuals (using Eq. (4)), vs. magnitude, of the observed and calculated parameters of PGA for BA, CB, and CY models. Different site soils are shown

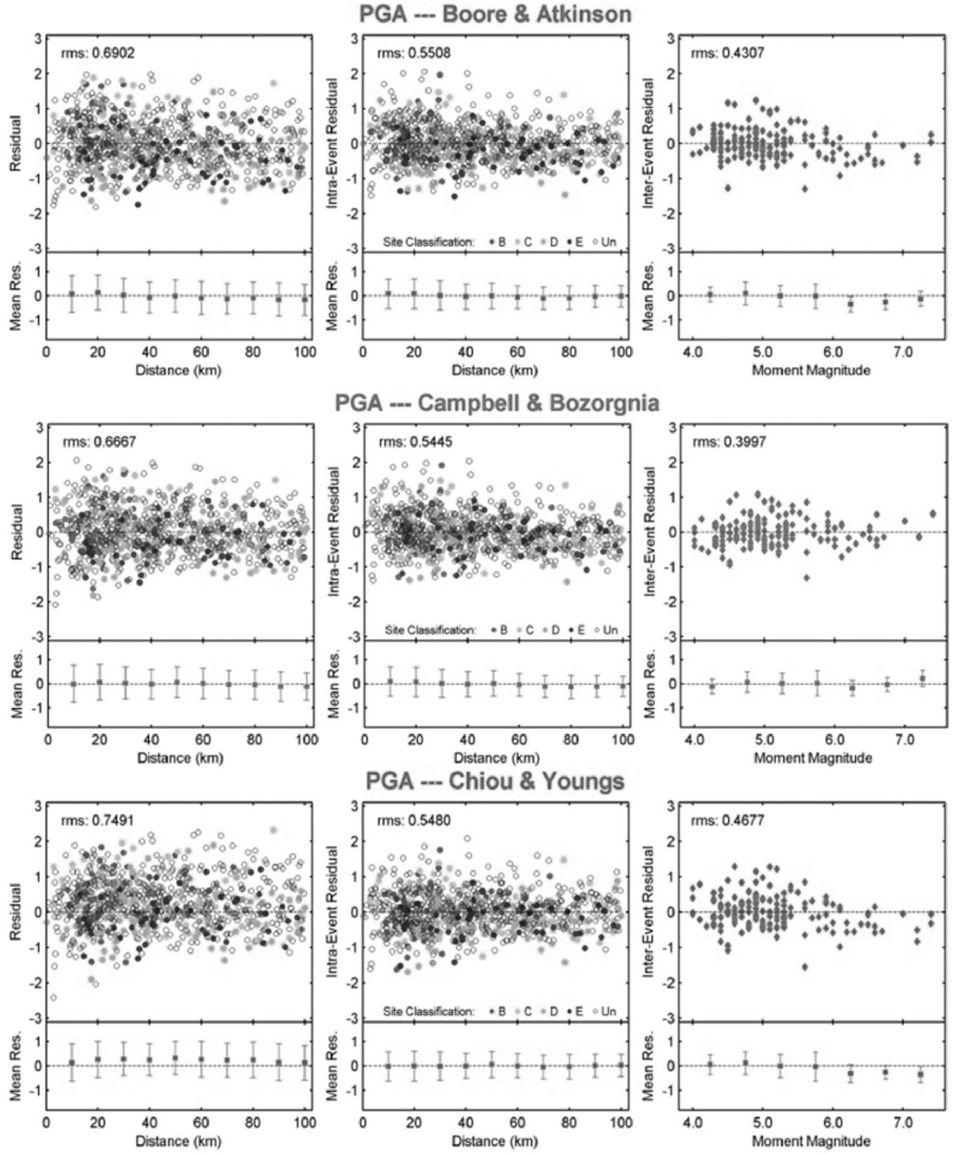

FIGURE 4 The residuals and intra-event residuals (using Eqs. (1) and (3)) vs. distance and inter-event residuals (using Eq. (4)), vs. magnitude, of the observed and calculated parameters of PGA for BA, CB, and CY models are shown. Different site soils are shown by different colors.

by different colors. While the residuals (Eq. (1)) and intra-residuals and their means for BA and CB models are similar and have uniform distributions around the zero base line, the corresponding residuals observed by CY model indicate that the PGA parameter in Iran is somewhat underestimated by this model. Inter-event residuals of PGA versus magnitude and their mean values in CB model are smaller than those shown by BA and CY models. These residuals tend to deviate from zero base line and become negative beyond magnitude 6.5 in both BA and CY models. This implies that CB model may give more unbiased estimates of PGA for larger magnitudes in Iran.

Figure 5 illustrates the residuals and intra-event residuals vs. distance and inter-event residuals, vs. magnitude, of the observed and calculated parameters of PGV for BA and CB models. GMPE for PGV has not been estimated in CY model. The residuals and intra-residuals and their means for BA and CB models are similar. But the inter-event residuals of PGV vs. magnitude and their mean values are not well distributed around the zero base line. They tend to become negative at magnitude less than 5 and then become positive for magnitude 6.5 and larger.

Figure 6 depicts the three different residuals and their means for 5%-damped PSA for period of 0.2 s using the three models. While the residuals and their means of the dataset versus distance in BA and CB models are fairly linear and show somewhat uniform distribution around the zero base-lines in BA and CB models, the corresponding residuals and their means in CY model show that the PSA values at this period are underestimated

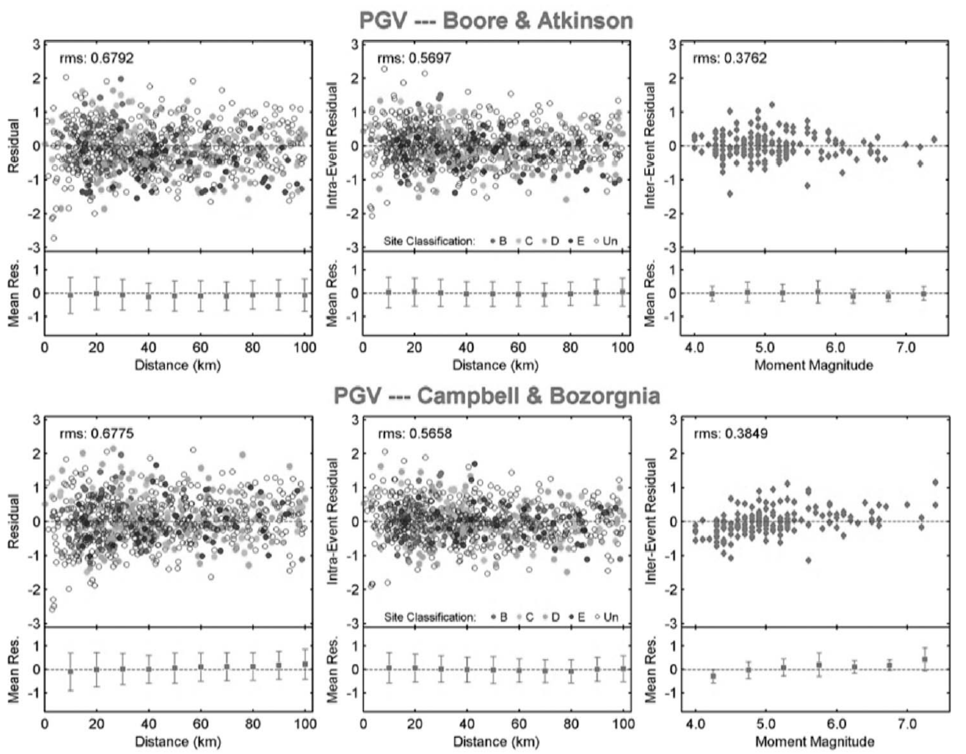

FIGURE 5 The residuals and intra-event residuals vs. distance and inter-event residuals, vs. magnitude, of the observed and calculated parameters of PGV for BA and CB models are shown. GMPE for PGV has not been estimated in CY model.

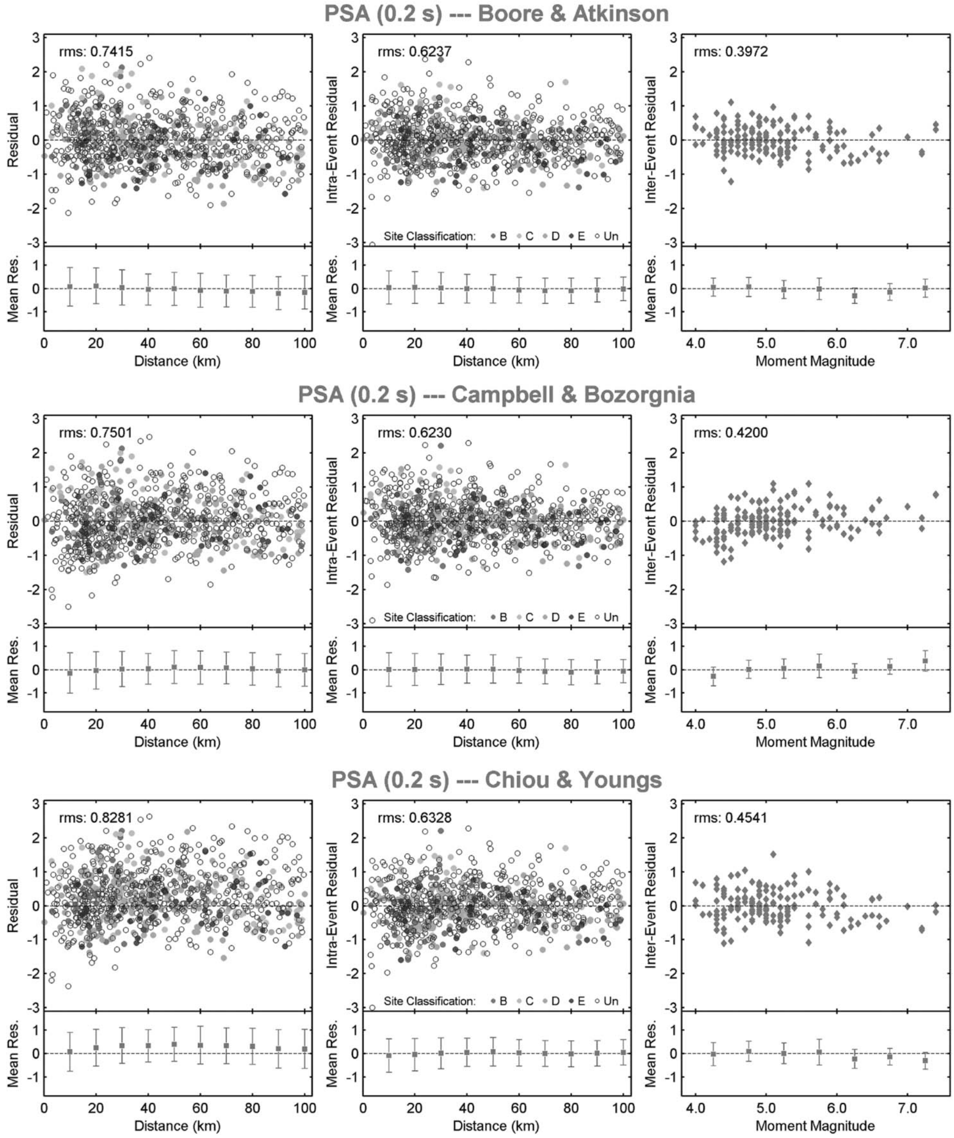

FIGURE 6 Three different residuals and their means for 5%-damped PSA for period of 0.2 s are shown using the three NGA models.

by this model. The inter-event residuals and their mean values show nonlinear behavior in all three models at larger magnitudes.

In Fig. 7, the PGA and PGV curves of the NGA models for two magnitudes of 6.5 and 7.5 are compared with the corresponding observed parameters for earthquakes with strike slip fault types and magnitude range between 6.5 and 7.5. The intra-event residuals are also shown in this figure. The PGV curve of M7.5 in CB model underestimates most of the PGV values of the events, with magnitudes larger than 7.0, which are registered at about 100 km from their sources. The small red circles of PGAs and PGVs shown at near source distances of about 1 km correspond to the PGA and PGV values of the motions recorded at Bam station during the 2003 Bam, Iran, earthquake. Except for the PGA

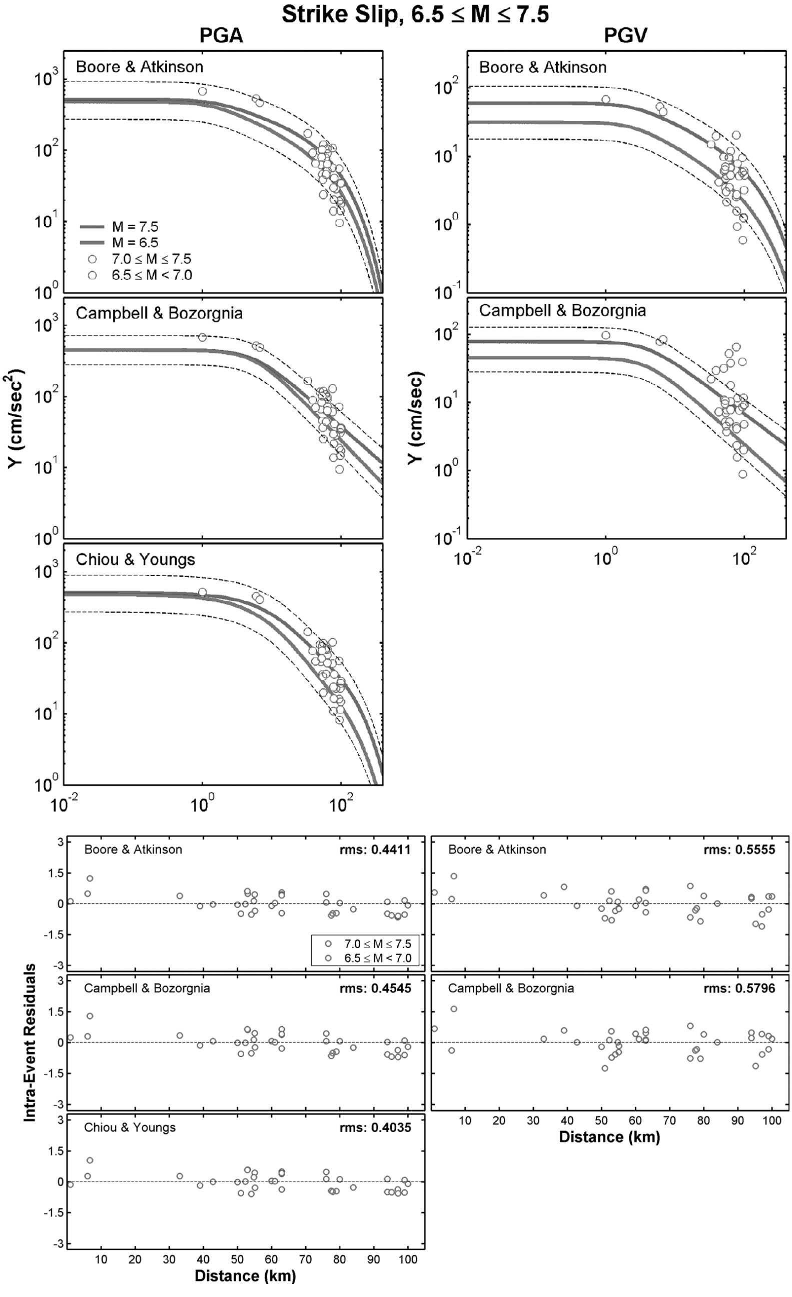

FIGURE 7 The PGA and PGV curves of the NGA models for two magnitudes of 6.5 and 7.5 are compared with the corresponding observed parameters for earthquakes with strike slip fault types and magnitude range between 6.5 and 7.5. The intra-event residuals are also shown.

curve of the CY model, the PGA and PGV values of this record noticeably exceed the values shown by the other curves. The exceptionally large values at this station were produced mainly by the effect of source directivity which was responsible for the total devastation of the Bam city in Iran. The PGA curve of CY model seems to fit the data better than BA and CB models at far distances.

In Fig. 8, the PGA and PGV curves of the NGA models for two magnitudes of 6.5 and 7.5 are compared with the corresponding observed parameters for earthquakes with reverse fault types and magnitude range between 6.5 and 7.5. The intra-event residuals are also shown in this figure. The PGA and PGV curves of M6.5 in BA and CB models both underestimate most of the PGA and PGV values of the events, with magnitudes larger than 6.5, which are registered at about 100 km from their sources. The PGA curve of CY model seems to fit the data better than BA and CB models at far distances. The small green circles of PGAs and PGVs shown at near source distances of about 3 km correspond to the PGA and PGV values of the motions recorded at Tabas station during the 1978 Tabas, Iran, earthquake. PGA and PGV values at this station exceed the values of the corresponding curves of M7.5 at least by one standard error. Similar to the case of the Bam earthquake, the large values of PGA and PGV were produced mainly by the effect of rupture propagation passing nearby Tabas station [Shoja-Taheri and Anderson, 1988] and causing a total devastation of this city in Iran. With the exception of PGA curves of CY model, the curves of BA and CB models overestimate the strong motion values at far distances.

In Fig. 9, RMS values of PSA parameters of Iran's dataset are compared with RMS values of PSA parameters using NGA dataset. Comparison between the RMS values of Iran and NGA dataset shows that while the RMS values of the NGA dataset vary increasingly with period from 0.45–0.68, the corresponding values of the Iran's dataset vary from 0.55 at short periods to 0.68 at the period of 0.5 s and then decrease to 0.48 at high periods. As a result, the RMS values of Iran's dataset is about 0.15 units larger than those of the NGA dataset from short periods up to 0.5 s and then gradually become about 0.15 units smaller at long periods.

Figure 10 compares the RMS values of different residuals (Eqs. (1), (2), and (4)) produced by NGA models for PSA periods of Iran's dataset. It is shown that the RMS level of the residuals are more or less similar for the NGA models except the RMS values of the residuals (Eq. (1)) of CY model which are somehow large than those of BA and CB at both ends of the period range.

3. Conclusions

In the regions with high seismic activity, any attempt toward earthquake hazard reduction needs to develop a set of attenuation equations which could appropriately represent the variable parameters of the strong motion data in that region. In a region, applicability of the attenuation equations for an unbiased evaluation of earthquake hazard reduction strongly depends on the extent of reliability of the information regarding the earthquake source parameters and site condition of the recording stations (e.g., magnitude, fault distribution, fault type, soil class).

It seems that the present information available on the Iranian strong-motion data is not as complete as the information on NGA dataset, especially in the near-source areas. As mentioned before, over 35% of the Iran's strong motion records are related to the events (mostly small and moderate earthquakes) for which no information on their fault types are available (see Table 2). In addition, as listed in Table 4, about 55% of the strong motion records correspond to the recording stations where no information about their site conditions was given. It is, therefore, reasonable to expect that the residuals and the corresponding RMS values of the Iran's dataset would naturally be larger than those values evaluated for NGA dataset. Nevertheless, the results indicate that the three NGA models we used in this study are generally applicable to the strong motion dataset of Iran within the acceptable level of errors. Comparison made between the RMS values of Iran

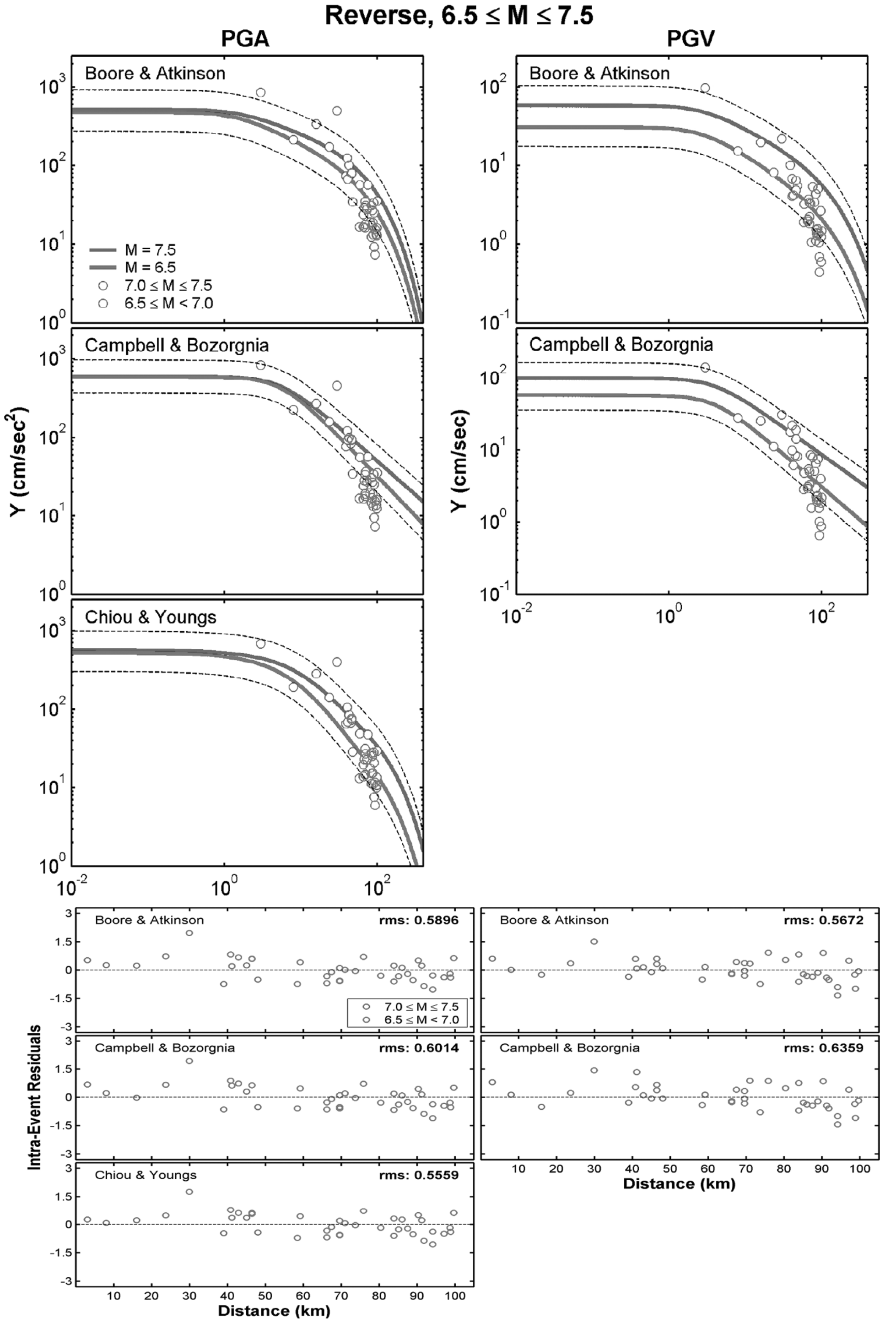

FIGURE 8 The PGA and PGV curves of the NGA models for two magnitudes of 6.5 and 7.5 are compared with the corresponding observed parameters for earthquakes with reverse fault types and magnitude range between 6.5 and 7.5. The intra-event residuals are also shown.

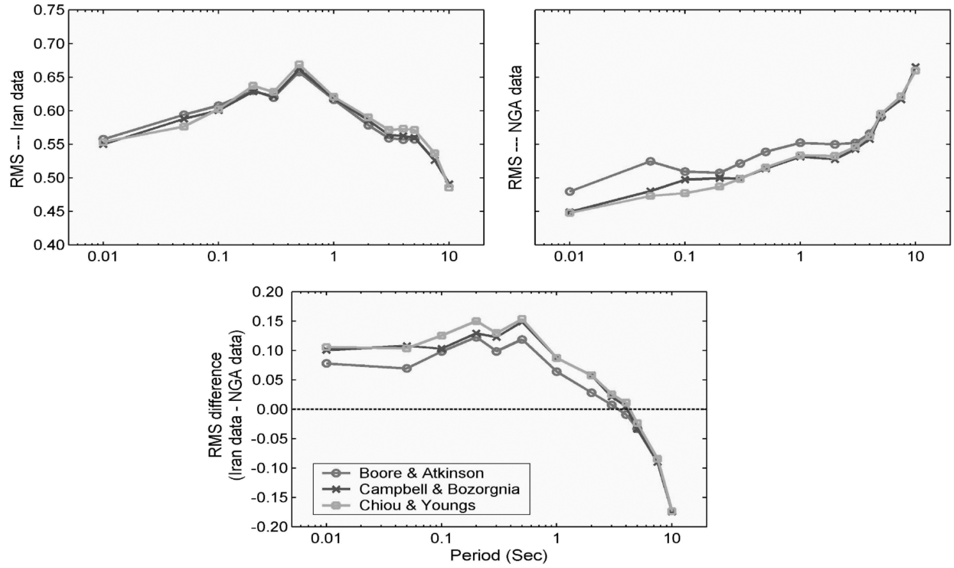

FIGURE 9 RMS values of PSA parameters of Iran's dataset are compared with RMS values of PSA parameters using NGA dataset.

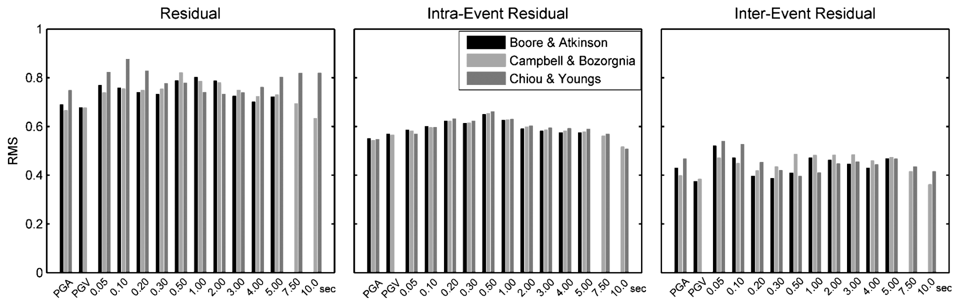

FIGURE 10 Comparison of the RMS values of different residuals (Eqs. (1), (2), and (4)) produced by NGA models for PSA periods of Iran's dataset.

and NGA dataset shows that while the RMS values of PSAs of the NGA dataset vary increasingly with period from 0.45–0.68, the corresponding values of the Iran's dataset vary from 0.55 at short periods to 0.68 at the period of 0.5 s and then decrease to 0.48 at high periods. As a result, the RMS values of Iran's dataset is about 0.15 units larger than those of the NGA dataset from short periods up to 0.5 s and then gradually become about 0.15 units smaller at long periods. We believe that the three NGA models we used in this study are generally applicable to the presently available Iranian dataset. NGA model of BA is somewhat more applicable than the other two models of CB and CY since in their model some of the details on the near source effects (e.g., effects of hanging wall and footwall, distance of the upper part of the fault rupture to the surface, and so on) which are required to include by in CB and CY models are excluded in their analysis. In general, BA and CB models show better fit to the Iranian dataset. It is to note that in future with larger collection of strong motion data and more detailed information on site conditions and faulting processes of earthquakes, an independent model similar to the NGA equations are needed to be developed for Iran.

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