Test of goodness of the NGA ground motion equations to predict the strong-motions of the 2012 Ahar–Varzaghan dual earthquakes in north-west of Iran

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Abstract-In the first part of this study, a set of 87 ground-motion records, with closest distance to the rupture plane (Rrup) less than 200 km and averaged shear-wave velocity over the top 30 meters of the subsurface (Vs30) between 175 to 1400 m/s, recorded during the 2012 Ahar-Varzaghan dual earthquakes(Mw_1=6.4, Mw_2=6.3) were taken into account in order to examine the predictive capabilities of the Next Generation Attenuation (NGA) Ground Motion Prediction Equations (GMPEs) via a set of comparative analyses and tests. The first applied methodto assess the performance of the NGA GMPEs is based on the intra-event residual analysis. The primary database (i.e. 87 records) was also used to develop an event-specific GMPE in the case of the Ahar-Varzaghan dual earthquakes by means of regression analyses. The derived event-

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specific GMPE has been compared with the NGA GMPEs for two different site conditions i.e. Vs30 > 375 m/s (rock site) and Vs30 < 375 m/s (soil site). The residual analysis results indicate that the NGA GMPEs perform better in predicting data recorded at rock sites compared to soil sites. For soil sites and at large periods (T=2.0 s), the observed spectral accelerations are over-predicted by the NGA GMPEs. Furthermore, in the second part of this study, in order to select the most adequate GMPEs, 14 strong-motion records from the 1997 Ardebil earthquake (Mw=6.1) were added to the primary database. The implementation of the LH and LLH methods, as modern likelihood based ranking assessment techniques, as well as the Nash-Sutcliffe index reveals that the NGA GMPEs show good compatibility at short-medium periods (T < 1.0 s) with the data recorded during the 2012 Ahar-Varzaghan dual and 1997 Ardebil earthquakes (i.e. 101 records). However, in the long-period range, the dispersion in the data does not allow the authors to drawa comprehensible conclusion.

Key words: Ground Motion Prediction Equation (GMPE), Next Generation Attenuation (NGA), Residual analysis, LH and LLH methods, Ahar-Varzaghan dual earthquakes, Ardebil earthquake, Iran

Introduction

An accurate prediction of expected ground-motion parameters plays an important role in the reliable assessment of any Seismic Hazard Analysis (SHA), particularly in specific regions with high levels of seismicity, e.g. Iranian seismic plateau. The Ground Motion Prediction Equations (GMPEs) generally predict ground-motion intensities, such as Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and response Spectral Acceleration (SA), as a functional form of magnitude, site-to-source distance, site condition, and other seismological parameters. In recent decades, numerous GMPEs have been developed to have more descriptive and complex parameters in particular forms. A comprehensive worldwide summary of GMPEs was given by J. Douglas in 2011, which includes the characteristics of 289 empirical GMPEs for the prediction of PGA and 188 empirical models for the prediction of elastic response spectral ordinates developed between 1964 to 2010 (Douglas, 2011).

In 2008, the Next Generation Attenuation project, which was initiated by the Pacific Earthquake Engineering Research (PEER) center, developed five new ground motion models through a comprehensive and highly interactive research program, for shallow crustal earthquakes (see Power *et al.* 2008). The NGA database, that has been used to develop the NGA GMPEs, is relatively large i.e. 3551 recordings from 173 earthquakes (A few Iranian events are also included in this database). These models are: Abrahamson and Silva (2008) (AS08), Boore and Atkinson (2008) (BA08), Campbell and Bozorgnia (2008) (CB08), Chiou and Youngs (2008) (CY08), and Idriss (2008) (I08). [A1]The characteristics of the NGA GMPEs are summarized in Table 1 including the applicableranges of magnitude, distance measure, and shear-wave velocity. It should be noted that the I08[A2] model only includes rock sites (assumed to be the sites with Vs30 ≥ 450 m/s). This significant difference isolates the Idriss ground motion model (2008) from the other models because it can only be applied to rock sites. Therefore, this model is excluded in this paper for further investigations. The NGA GMPEs are worldwide ground motion prediction models and the only constraint is that the region under investigation should be tectonically active with earthquakes occurring in the shallow crust. Therefore, several quantitative comparisons of the NGA GMPEs have been accomplished by researchers for different regions and scenarios during last decade (Bindi *et al.,* 2006; Scassera *et al.,* 2009;

Shoja-Taheri *et al.,* 2010; Kaklamanos and Baise, 2011; Mousavi *et al.,* 2012). However, there are some studies with different results on the NGA GMPEs application for the Iranian plateau data sets (Shoja-Taheri *et al.,* 2010; Mousavi *et al.,* 2012). An inherent reason for this inconsistency may come from the fact that the NGA models are considerably more complicated than previous GMPEs. They usually require several input parameters (Kaklamanos *et al.,* 2011) which are not precisely known in the case of latest earthquakes, at least in the case of Iranian earthquakes. Estimating unknown input parameters, when implementing the NGA GMPEs in engineering practice, is obviously a crucial task to make an appropriate judgment on their performance (Kaklamanos *et al.,* 2011). Therefore, one solution is to evaluate the NGA models for new events in which their seismic characteristics are very well known (see e.g. Wang *et al.* 2010 for the 2008 Wenchuan earthquake; Massa *et al.* 2012 and Bindi *et al.* 2006 [A3]for the 2009 L'Aquila earthquakes; Liao and Meneses 2012 for the 2010 El Mayor–Cucapah earthquake and Stewart *et al.* 2013 for the 2011 Tohoku-oki earthquake, and also the subject of the current study).

The Azerbaijan province, which is located in north-west of Iran, is one of the most active seismic regions in the country. It has experienced many seismic events during the historical and instrumental periods. However, before the Ahar-Varzaghan 2012 dual earthquakes, and since the early 1980's when the first accelerometers were installed in Iran, only one earthquake larger than M = 6 has been well recorded instrumentally in this region (the 1997 Ardebil earthquake). This scarcity of strong-motion data of moderate to large magnitude earthquakes has severely hampered the reliable prediction of seismic hazard in the region.The recent dual earthquakes with magnitudes Mw=6.4 and Mw=6.3 struck the Ahar-Varzaghan area in the Azerbaijan province on August 11, 2012 (Copley *et al.,* 2013). The earthquakes caused about 327 casualties and destroyed more than 20 villages severely, and damaged many buildings in the Ahar and Varzaghan towns located around 20 km of the main shocks. The addition of the Ahar-Varzaghan dual earthquakes data provides a unique opportunity for researchers to study the characteristics of strong-motions for moderate to large magnitude earthquakes ($M > 6$) in north-west of Iran. Also, it is worth to say that we usually refer to a pair of similarly sized earthquake shocks that occur relatively closely spaced in time and location as an earthquake "doublet". This is distinct from the normal pattern of earthquake aftershocks. Usually a doublet is defined, as a pair of events with a magnitude difference of no more than 0.2 to 0.4 units, spatial separation smaller than 100 km, and temporal separation of a few years, depending on how large the considered events are (Astiz and Kanamori, 1984). Kagan and Jackson (1999) specified doublets as pairs of large earthquakes with centroids (center of the deformation release) closer than their rupture size and occurring within a time interval shorter than the recurrence time inferred from plate motion. In the current case, although the second earthquake may be described as an aftershock, it shows that plenty of elastic energy remained after the first event (see Kagan and Jackson 1999 for similar cases).

Therefore, this earthquake doublet has been comprehensively investigated in this study in order to evaluate the NGA GMPEs. The data set is described in the next section and an event-specific GMPE has been developed usingthe doublet records. Finally, a variety of goodness-of-fit tests are provided in order to draw a conclusion on the applicability of the NGA GMPEs in the region. As a matter of fact, GMPEs relate ground-motion parameters (e.g. PGA, SA) to three different components, namely, seismic source parameters, local site conditions, and propagation path effects (Kaklamanos *et al.,* 2011). The first component relates to the size and source mechanism of the event.The second component describes the effect of the upper hundreds of meters of rock and soil and the surface topography at the site, and the last one describes the decrease in the amplitude of seismic waves with distance. It is worth noting that a basic assumption in the NGA models is that scaling of the spectral values with distance out to about 70 km is the same for shallow earthquakes in active crustal regions around the world. This assumption allows us to combine data from different parts of the world into a single model. At distances larger than 70 km, we know that there are strong regional differences in the attenuation. Here, the LH method of Scherbaum *et al.* (2004) has been applied in the case of two distance bins, i.e. less than 70 km and more than 70 km. This allows us to precisely examine the effect of differences in the anelastic decay in different regions (i.e. those of the NGA database and the north-west of Iran). To enrich the database, also 14 records from the 1997 Ardebil earthquake was added when applying statistical tests (i.e. the LH, LLH and the Nash–Sutcliffe model efficiency coefficient).

Data Set

The strong-motions of the Ahrar-Varzaghan dual earthquakes were recorded at more than 140 free-field stations of the national Iranian Strong Motion Network (according to the Building and Housing Research Center, BHRC website, last accessed December 2012). All of the strong-motion data, obtained during the Ahar-Varzaghan dual earthquakes, were recorded by digital Kinemetrics SSA-2 accelerographs. Ground motions with Rrup less than 200 km were implemented in this study in order to investigate the predictive capabilities of the NGA GMPEs. Aftershock locations indicate that two main shocks ruptured the ~25 km long Ahar fault characterized by strike ~N270°E and dip ~80-90°N. The second large earthquake had a very similar magnitude (Mw 6.3) and occurred on 11 August at 12:34.35 UT, i.e. 12 minutes later, on a parallel fault located ~1 km south of the Ahar fault (see Figure 1). The first event was close to pure strike-slip, and the second was an oblique combination of thrust and strike-slip motion.

Various criteria can be used to define rock and soil sites. The most widely used criteria are based on the average shear-wave velocity over the top 30 m, Vs30 (available for 35 stations that recorded 58 three-component records). Alternatively, a site can be classified in terms of its fundamental resonance frequency. Such an approach has been proposed as a proxy of Vs30 by Zare *et al*. (1999) and recently modified by Ghasemi *et al.* (2009a) for the Iranian plateau. The method has been used here to classify stations with no information about Vs30 (i.e. 16 stations that recorded 29 three-component records). Figure 2 shows the distribution of Vs30 versus the distance measure.Therefore, in this study, 87 ground-motion records with Rrup less than 200 km and Vs30 between 175 to 1400 m/s, recorded during the two earthquake events of Ahar-Varzaghan 2012, with the averaged moment magnitude (Mw) of 6.35, were used to assess the capability of the NGA GMPEs developed for shallow crustal earthquakes in tectonically active regions (see Figure 1). The name, code number, fault distance (Rjb) and Vs30 of these stations are listed in the Appendix Table A1. The uncorrected acceleration time series, recorded by a given station, were corrected for the instrument response and baseline, following a standard algorithm (Trifunac and Lee, 1973). Multi-resolution wavelet analysis (Ansari *et al.,* 2010) was used to remove undesirable noise from the raw signals. The capabilities of the modified wavelet de-noising method in correction of highly noisy acceleration records were studied in detail by Ansari *et al.* (2010). According to Ansari *et al.* (2010) in the conventional filtering method, some low and high frequency components of the motion are removed from the signal and other frequency components of the signal remain unchanged and it is assumed that the energy of the noise is concentrated only in the low and high frequencies. However, in applying the wavelet de-noising method, it is assumed that it is possible to have noise in all frequency components of the motion, just like the case of white noise.

Table 2 summarizes the input parameters for the NGA models obtained from various sources. A finite-fault plane is assumed and all distance calculations are based on the geometry of the fault plane relative to the station location. The strike of the fault is similar to the value reported by Copley *et al.* (2013) for the first Ahar-Varzaghan event, and the values reported by the Harvard Seismology for the second Ahar-Varzaghan and the 1997 Ardebil events. These are also compatible with the surface traces (Copley *et al.,* 2013; Hessami and Jamali, 2006). The focal depth was used to fix the fault plane position for all three cases, in the vertical dimension.

The Ahar-Varzaghan 2012 event-specific GMPE

The authors have proposed an event-specific GMPE in this study in order to have a logical and reasonable basis for the purpose of comparison between the selected NGA GMPEs. The functional form of the event-specific was chosen based on previous studies with concerning about the validation of GMPEs (Mousavi *et al.,* 2012; Ghasemi *et al.,* 2009b). The final form of the event-specific GMPE is similar to Ghasemi *et al.* (2009b) and the optimized coefficients show good similarity with the original form of GMPE. Eq.(1) indicates the functional form of the event-specific GMPE with the optimized coefficients derived fromthe 87 free-field recordings with Rrup distances and Vs30 ranging between (and about) 10 to 200 km and 175 to 1400 m/s, respectively.

$$\mathrm{Ln}(Y) = a_0 + a_1 \mathrm{Ln}(Rrup + a_2) + a_3 SR + a_4 SS + \varepsilon \qquad (1)$$

where, Y is the simple geometric mean of5% damped spectral acceleration of two horizontal components in g unit for period T ranging between 0.0 to 3.0 s. The variables SR and SS take on values as: SR=1 and SS=0 for rock sites and SR=0 and SS=1 for soil sites. In the current study, the simple geometrical mean has been used for all GMPEs since some studies have shown that the ratio of this measure of the horizontal component of the ground motion over the measure of the geometric mean which is used in the NGA models (GMRotI50, Boore et al. 2006), is near unity at all periods (Beyer and Bommer 2006).Although the NGA GMPEs go beyond 3.0 s, their database at long periods islimited (Abrahamson and Silva, 2008). Also the computedvalues of SA for long periods are more sensitive to noise (Boore and Atkinson, 2007). Accordingly, in this paper, the analysis is focused on spectral periods up to 3.0 s (see Kaklamanos and Baise, 2011 for a similar case). It should also be emphasized that for most engineering applications the adequate periods are between 0.1 and 3.0 s.

In this study, sites were grouped into two categories including rock and soil. The site classification is the same as the ground categories specified by the Iranian code of practice for standard seismic resistant design of buildings (Standard No. 2800). Site classes I and II with Vs30 $\geq$ 375 m/s were combined together and assumed as rock sites, and categories III and IV with Vs30 < 375 m/s were combined together and considered as soil sites. Constant coefficients a_0, a_1, a_2, a_3, and a_4 were obtained by regression analyses and ε is an error term. The results of the regression analysis are shown in Table 3 and the median spectral accelerations, predicted by Eq. (1), are shown in Figure 3 for PGA and spectral ordinates in 0.5, 1.0, and 2.0 s periods. In Figure 3, a single Vs30, for both rock and soil site classification, was used to obtain the predictive curve for each period; hence, it cannot reveal the actual local site conditions for different seismic stations. For this reason, as it is shown in Figures 4 and 5, the intra-event residuals of the derived event-specific GMPE [Eq. (1)] were calculated for each ground motion station to reflect the specific site-to-source distance measure (Rrup) and local site conditions (Vs30). In order to quantitatively identify the trend of residuals against Rrup and Vs30, a linear regression model is applied (Azarbakht *et al.,* 2014). The p-values for testing the null hypothesis about the likely existence or nonexistence of bias in estimations are shown on the upper left corner of Figures 4 and 5. According to the determined p-values[A4], the residuals show no clear trend for Rrup and Vs30 through the available ranges, which emphasize that the obtained constant values in Table 3 provide an acceptable representation of the 2012 Ahar-Varzaghan dual earthquakes dataset.

The comparison of the standard deviation from the derived event-specific model of 2012 Ahar earthquake events, by means of regression analyses and the four intra-event standard deviations of the NGA GMPEs, are shown in Figure 6. In the short period range, less than about 1.0 s, the standard deviations of the event-specific GMPE [Eq. (1)] and NGA GMPEs are practically the same and show good compatibility with each other. However, in the long-period range, beyond 1.0 s, the event-specific model has larger standard deviation in comparison with the NGA models.

Comparison of event-specific model with the NGA GMPEs

Figure 7 shows the comparison of the observed spectral accelerations, i.e. PGA, SA (T=0.5, 1.0, 2.0 s, 5% damping) with the median predictions from the four NGA GMPEs in the case of Vs30=300 and 750 m/s, respectively. As it is clear in Figure 7, for T=0.0, the observed spectral ordinates are under-predicted by the NGA GMPEs at Rrup less than 50 km and over-predicted at Rrup beyond 50 km. This trendis observed at soil sites with Vs30 less than 375 m/s and rock sites with Vs30 more than 375 m/s. Furthermore, Figure 7 shows that, for the rest of periods (T=0.5, 1.0, and 2.0 s) and Vs30 less than 375 m/s, the observed spectral accelerations are over-predicted by the NGA GMPEs. For rock site and period equal to 0.5 s, the AS08 and CY08 models, respectively, over-predicts and under-predicts the spectral ordinates and the CB08 and BA08 models show good compatibility with the event specific trend. For T=1.0 s, specifically for sites with Vs30 less than 375 m/s, the NGA GMPEs over-predict the spectral ordinates. On the other hand, for rock sites the NGA GMPEs under-predict the spectral ordinates in the range of Rrup more than 30 km in the case of the CB08 and CY08 models and Rrup more than 100 km in the case of the BA08 and AS08 models. Finally, for T=2.0 s for soil sites, the NGA GMPEs predict approximately the same trends except the BA08 model that over-predict the spectral ordinates. Also, for rock sites, the observed spectral accelerations at T=2.0 s are meaningfully under-predicted by the NGA GMPEs. On closer scrutiny, the NGA GMPEs predictions are more compatible with the observed spectral accelerations at rock sites with Vs30 beyond 375 m/s.

Comparison of residuals with the NGA GMPEs

The comparison of intra-event residuals versus Rrup and Vs30 are, respectively, shown in the case of PGA in Figures 8 and 9. As abovementioned, for comparing the trend of residuals versus Rrup and Vs30, a linear regression model was applied. The mentioned p-values for the case of PGA in Figures 4 and 5 are comparable with Figures 8 and 9. As seen in Figure 8, partly positive intra-event residuals between (and about) 10 and 50 km were observed in the case of the

CB08 model which means the CB08 model under-predicts the observed spectral accelerations. However, the CB08 model is faced to comparatively negative intra-event residuals (over-predicts the observed spectral accelerations) between 50 and 200 km. Furthermore, the AS08 follow the same trend between 10 and 100 km. Moreover, the BA08 model tends to have a pronounced negative trend versus Rrup. Among the NGA GMPEs, the CY08 model is more stable with higher p-value; nonetheless, it has positive intra-event residuals with respect to Rrup as seen in Figure 8. By comparison between Figure 4(a) and Figure 8, the NGA GMPEs show more bias, in the case of PGA, against the event-specific GMPE model of the 2012 Ahar-Varzaghan earthquakes versus Rrup.

Figure 9 shows the distribution of intra-event residuals versus Vs30 from 175 m/s to 1400 m/s for PGA. In general, with comparison Figure 5(a) in the case of PGA, except CY08 model, the observed spectral accelerations are over-predicted by the NGA GMPEs at Vs30 less than ~750 m/s. However, they are under-predicted [A5]at Vs30 beyond almost ~750 m/s. Also, it is observed that the intra-event residuals show more bias with respect to Vs30 than with the Rrup parameter.

The intra-event residuals versus spectral periods are shown in Figure 10. As seen in Figure 10, the period dependence of the intra-event residuals reveals that the AS08 model has better estimation than the other NGA GMPEs. Moreover, the BA08 and CB08 models over-predict the spectral ordinates for periods less than 0.5 s. On the other hand, CY08 completely under-predict the spectral ordinates.

Goodness-of-Fit Measures

Goodness-of-fit statistics were utilized in order to quantify the resemblance between the model predictions with the observed ground-motion records. The first employed statistical method, as part of the comparison in this study, is the Nash-Sutcliffe model efficiency coefficient [A6](Nash and Sutcliffe, 1970, Yaghmaei-Sabegh, 2012). The E value is given in Eq. (2):

$$E = [1 - \frac{\sum_{i=1}^{N} (Ln\,Y_i - Ln\,\hat{Y}_i)^2}{\sum_{i=1}^{N} (Ln\,Y_i - \overline{Ln\,Y})^2}] \times 100\% \qquad (2)$$

where N is the total number of ground-motion predictions, the observed values (PGA, SA, etc.) are denoted by Y_i, the predicted median values are denoted by $\hat{Y}_i$, and the mean of the logarithms of the observed values is denoted by $\overline{Ln\,Y}$. The higher values of E reveal better agreement between observations and predictions.

This criterion was applied to strong-motion records from the 2012 Ahar-Varzaghan and 1997 Ardebil events. As mentioned before, the 1997 Mw 6.1 Ardebil earthquake is the only well-recorded large earthquake (M > 6), before the Ahar-Varzaghan dual events, since installation of strong-motion network in theregion. Hereafter, 14 strong-motion records from this well-recorded event were added to the database in order to increase the robustness of results (see Figure 1, Table 2 and Appendix Table A1 for details).

The results of the Evalues are shown in Table 4 for the representative periods T=0.0, 0.5, 1.0, and 2.0 s. The NGA GMPEs show good compatibility at short to medium periods (T < 1.0 s) with the data recorded during the Ahar-Varzaghan dual and Ardebil earthquakes; also the AS08 model is ranked first among the other models.

Although, the study of intra-event residuals distribution and the coefficient of efficiency (E) adequately quantify the prediction accuracyof the NGA GMPEs, it does not take into consideration the standard deviation of the model (Kaklamanos and Baise, 2011). Therefore, two additional statistical approaches are applied in order to evaluate the NGA GMPEs i.e. the LH and LLH methods (Scherbaum *et al.,* 2004 and 2009). The median LH value based on the likelihood method, which has been introduced by Scherbaum *et al.* (2004), wasused to assess how well the aleatory variability (sigma) of the observations is predicted by the nominated GMPEs. The LH value for a single ground-motion prediction, by assumption of zero mean and unit variance, is given in Eq. (3):

$$LH\left(\left|Z_0\right|\right) = Erf\left(\frac{\left|Z_0\right|}{\sqrt{2}}, \infty\right) = 1 - Erf\left(\frac{\left|Z_0\right|}{\sqrt{2}}\right) \qquad (3)$$

$$Erf\left(Z_0\right) = \frac{2}{\sqrt{\pi}} \int_0^{Z_0} e^{-t^2}\, dt \qquad (4)$$

where Erf(|Z_0|) is the error function, given by Eq. (4) and Z_0 is the normalized model residual. As the ground-motion models are commonly expressed as the natural logarithmic quantities, the residual is defined as the subtraction of the natural logarithmic-model predictions from the natural logarithms of the observed values, divided by the corresponding standard deviations of the natural logarithmic model:

$$r = \frac{Ln\left(SA_{obs}\right) - Ln\left(SA_{pre}\right)}{\sigma_{SA}} \qquad (5)$$

where, SA_{obs} corresponds to the observed acceleration response spectra in a specified period, and SA_{pre} and σ_{SA} are the mean and the standard deviation of the predicted response spectra, respectively, by using a given ground motion model. Ideally, the defined residual is normally distributed with zero mean and unit variance.If the model assumptions (normalized residuals having zero mean and unit variance) are matched exactly, the LH values for a subset of predictions should be uniformly distributed between 0 and 100 percent. If the sample distribution follows a perfect standard normal distribution with the zero mean and the unit variance, then, the corresponding LH has median value approaches 50%. By using the LH distribution in combination with a few simple goodness-of-fit measures, Scherbaum *et al*. (2004) have proposed a sufficient description to judge on the capability of different GMPEs to match with an existing data set. In this case, the GMPEs are categorized into four main categories, i.e. A, B, C, and D according to this scheme (see Table 5 for details).

In this paper, for the above-mentioned three best-recorded earthquakes in north-west Iran, the LH method has been applied in order to rank the NGA GMPEs into four classes i.e. A, B, C, and D by using the intra-event residuals as well as the intra-event standard deviations. The results of the LH values are shown in Table 6 for the selected periods T=0.0, 0.5, 1.0, and 2.0 s.

The goodness-of-fit-measures in this approach are: the median LH values, the median, mean and standard deviation of the normalized residuals which are, respectively abbreviated as MEDLH, MEDNR, MEANNR, and STDNR in this paper. For determining the corresponding standard deviations of these measures (σ) the bootstrap technique through data re-sampling was performed (Efron and Tibshirani, 1993). By using these measures and based on the scheme presented in Table 5, the NGA GMPEs were ranked in the categories A, B, C, or D in the third column of Table 6.

The analysis of the results in Table 6, for all periods, indicates that the NGA GMPEs are ranked as A and B in short periods ($T \leq 1.0$ s) which indicates good compatibility between the

NGA GMPEs and the recorded data of the Ahar-Varzaghan dual and Ardebil events in north-west of Iran.

Furthermore, the LLH criterion as an information-theoretic based approach, which has been introduced by Scherbaum *et al.* (2009), was used in order to compare the predictive capabilities of the NGA models. The average sample log likelihood (LLH) has been calculated for each of the considered periods, one by one using Eq. (6). Rankings ofthe ground motion models according to the mean LLH values are presented in Table 7 for different periods. Additionally, in order to express what degree the data support or reject a model with respect to the state of non-informativeness, data support index (DSI) is applied by Eq. (7) (Scherbaum *et al.,* 2009; Delavaud *et al.*, 2012). Tables 7 and 8[A7] present the results of the LLH values and compatible weights to the NGA GMPEs, respectively.

$$LLH(g,x) := -\frac{1}{N}\sum_{i=1}^{N}\log_2(g(x_i)) \quad \text{[A8]} \qquad (6)$$

$$DSI_i = 100\frac{w_i - w_{unif}}{w_{unif}} \qquad (7)$$

$$w_i = \frac{2^{-LLH(g_i,x)}}{\sum_{j=1}^{K} 2^{-LLH(g_j,x)}} \quad \text{[A9]} \qquad (8)$$

[A10]in Eq. (7), $w_{unif} = \frac{1}{M}$ and M is the number of GMPEs. The results of the LLH criterion are precisely comparable [A11]with the results of the E values. The AS08 model which is located in top levels of the ranking by the E and LLH methods belongs to category A and B in short to medium periods based on the LH results; however, the obtained results to some extent are different from some previous studies (see e.g. Yaghmaei-Sabegh 2012). On the other hand, the BA08 and AS08 models are ranked as the most appropriate predictive models for the three studied events.

The NGA models were developed for distances less than 200 km; therefore, using them beyond this range is not appropriate. Moreover, using the NGA GMPEs for R > 70 km results in an unrealistic attenuation rate for different seismic regions that have quality factors (Q factor) differs from that of the *host region*. In this study, in order to have more informative residuals analysis, the dataset was separated into two distance bins: 0 – 70 km, and 70 – 200 km; with respect to this point, the LH method was independently applied for four the NGA GMPEs on the both mentioned subsets. On closer scrutiny, the results show relatively good consistency of the selected GMPEs at both short and large distances. The statistical measurements of the LH values for different periods (T = 0.0, 0.5, 1.0, and 2.0 s) are shown in Tables 9 and 10, respectively. A comparison between Tables 9 and 10 demonstrates that the NGA GMPEs result in more realistic outputs for large distances (Rrup > 70 km), in the case of short periods. However, for short distances (Rrup < 70 km) the LH results, just for a finite range of periods, are acceptable and in the most of periods do not show adaptable results.

Discussions and Conclusions

The analysis of the residuals, versus different seismic parameters, between the observed spectral accelerations and the median predictions of spectral accelerations by the NGA GMPEs have formed a foundation to obtain logical judgment on the performance of the NGA GMPEs for the 2012 Ahar-Varzaghan dual earthquakes. The interpretation of the predictions by the NGA GMPEs confirms that the observed spectral acceleration for soil sites with Vs30 less than 375 m/s are generally over-predicted (except PGA). It is worth to mention that, generally, the median predictions of spectral accelerations by the NGA GMPEs for rock sites with Vs30 larger than 375 m/s are close to each other, and providebetter estimations than in the case of soil sites. In this study, both the distance and the shear wave velocity treatments were investigated by assessing trends of intra-event residuals versus distance measure (Rrup) and site conditions (Vs30). The negative trend through the intra-event residuals versus Rrup indicates that, by increasing the distance measure, the NGA GMPEs models (except CY08) over-predict the spectral ordinates. The positive trend of the intra-event residuals versus Vs30 also indicates that, by increasing Vs30, the NGA GMPEs models under-predict the spectral ordinates. Moreover, the Nash-Sutcliffe coefficient of efficiency, LH, and LLH methods were used as robust schemes to examine the performance of the NGA GMPEs against the recordings from the 2012 Ahar-Varzaghan dual earthquakes and 1997 Ardebil earthquake. The LH method indicates that the NGA GMPEs for short periods are almost ranked as A and B models. Moreover, the results of LLH criterion are precisely comparable with the results of E values. Accordingly, the NGA GMPEs show good compatibility along with the 2012 Ahar-Varzaghan earthquake and 1997 Ardebil earthquake events for short periods. It is worth mentioning that several previous publications have shown that the adequacy between a model and observations depends on the period considered (see e.g. Beauval *et al.* 2012, Delavaud *et al.* 2012). Also,in order to study the path effects, more specifically, the database was divided into short distance (Rrup< 70 km) and distances larger than 70 km.The misfits of the NGA GMPEs are clear in both cases as seen in Tables 9and 10. At distances larger than 70 km, we know that there are strong regional differences in the attenuation and the NGA models was intended to be applicable to the western US (mainly California). However, it is worth to say that some studies have shown similarity between attenuation characteristics of two regions (i.e. California and Iran; see Nuttli 1980; Chandra *et al.* 1979). Therefore, it is not surprising that we have found a slightly better compatibility between the NGA GMPEs and our database at larger distances (Rrup>70 km) where the event-specific source effects became weaker and the local attenuation characteristics of the region dominate the behavior of recorded motions.

Finally, as a considerable number of papers have been devoted to the study of applicability of GMPEs to various seismotectonic regions (e.g. Douglas, 2004; Stafford *et al.,* 2008; Scasserra *et al.,* 2009; Delavaud *et al.,* 2012; Massa *et al.,*2012, Mousavi *et al.,* 2012), it is possible to compare the results of these studies with those obtained here. Douglas (2004) found more rapid distance attenuation in Europe than California by using the approach called analysis of variance. Stafford *et al.* (2008), based upon the application of the likelihood approach of Scherbaum *et al.* (2004), claimed that for most engineering applications, the NGA models may confidently be applied within Europe. Scasserra *et al.* (2009), by adopting a method in which specific attributes of the GMPE (in particular magnitude scaling, distance scaling, intra-event dispersion, and site effects) are examined relative to the data, found that the magnitude scaling implied by the Italian data is compatible with four NGA relations. However, the Italian data seems to attenuate faster than implied by the four NGA GMPEs at short periods (see also Massa *et al.,* 2012). On the basis of these findings, they recommended to use the NGA relationships, with minor modifications, to evaluate ground motions for seismic hazard analysis in Italy. More recently, the ability of 11 GMPEs to predict ground-motion in different active shallow crustal regions worldwide have been investigated by Delavaud *et al.* (2012). One of the results of their study is that some nonindigenous models present a high degree of consistency with the data from a target region.

In this context, regarding the issue of the applicability of the NGA GMPEs to north-west of Iran (a region outside their zone of origin or host region) it is difficult todraw a general conclusion, keeping in mind that this is a limited test using data from only three well-recorded events of approximately similar size. During evaluation of predictive capabilities of the NGA models for past earthquakes, there is also a large variability in the average residual for individual earthquakes (inter-event residual) which should be considered (see e.g. Boore and Atkinson 2007). The issue eventually can be solved as more comprehensive data became available for the region.

Data and Resources

The ground motion records were provided by the Building and Housing Research Centre (BHRC), Iran (http://www.bhrc.ac.ir/portal/, last accessed December 2012). The Global Centroid Moment Tensor Project database was searched using www.globalcmt.org/CMTsearch.html (last accessed December 2012). Regarding the crustal structure of the region, the Global Crustal Model CRUST2.0 has been used (Institute of Geophysics and Planetary Physics. The University of California, San Diego; 2001. http://igppweb.ucsd.edu/~gabi/rem.html, last accessed December 2012).

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References

Abrahamson, N. A., and W. J. Silva (2008). Summary of the Abrahamson & Silva NGA ground-motion relations, *Earthq. Spectra* **24,** 67-97.

Ansari, A., As. Noorzad, H. Zafarani, and H.Vahidifard (2010). Correction of highly noisy strong motion records using a modified wavelet de-noising method, *Soil Dynamics and Earthquake Engineering* **30**(11), 1168-1181.

Astiz, L., and H. Kanamori (1984). An earthquake doublet in Ometepec, Guerrero, Mexico, *Physics Earth and Planetary Interiors*. **34**, 24-45

Azarbakht, A., S. Rahpeyma, and M. Mousavi (2014). A New Methodology for Assessment of the Stability of Ground-Motion Prediction Equations, *Bull. Seismol . Soc. Am.***104(3)**.

Beauval C., H. Tasan, A. Laurendeau, E. Delavaud, F. Cotton, Ph. Guéguen, and N. Kuehn (2012). On the testing of ground-motion prediction equations against small magnitude data, *Bull. Seismol. Soc. Am.***102**, 1994-2007.

Beyer K., J. J. Bommer (2006). Relationships between median values and between aleatory variabilities for different definitions of the horizontal component of motion, *Bull. Seismol. Soc. Am.***96**, 1512–1522.

Bindi, D., L. Luzi, F. Pacor, G. Franceschina, and R. R. Castro (2006). Ground-Motion Predictions from Empirical Attenuation Relationships versus Recorded Data: The Case of the 1997–1998 Umbria-Marche, Central Italy, Strong-Motion Data Set, *Bull. Seismol. Soc. Am.***96**, 984-1002.

Boore D. M., and G. M. Atkinson (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 sec and 10.0 sec, *Earthq. Spectra* **24,** 99-138.

Boore, D. M., and G. M. Atkinson (2007). Boore-Atkinson NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters, PEER Report No. 2007/01, *Pacific Earthquake Engineering Research Center*, University of California, Berkeley, 242 pp.

Boore D. M., J. Watson-Lamprey, and N. Abrahamson (2006). GMRotD and GMRotl: Orientation independent measures of ground motion, *Bull. Seismol. Soc. Am.***96,**1502-1511.

Campbell, K. W., and Y. Bozorgnia (2008). NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01sec to 10 sec, *Earthq. Spectra* **24,** 139-171.

Chandler, A. M., N. T. K. Lamb, and H. H. Tsang (2005). Shear wave velocity modelling in crustal rock for seismic hazard analysis, *Soil Dyn. Earthq. Eng.* **25,** 167–185.

Chandra V. J., G. McWhorten, A. Nowroozi (1979). Attenuation of intensities in Iran. *Bull. Seismol. Soc. Am.* **69**, 237–50.

Chiou, B. S., and R. R. Youngs (2008). An NGA model for the average horizontal component of peak ground motion and response spectra, *Earthq. Spectra* **24,** 173-215.

Copley, A., M. Faridi, M. Ghorashi, J. Hollingsworth, J. Jackson, H. Nazari, B. Oveisi, and M. Talebian (2013). The 2012 August 11 Ahar earthquakes: consequences for tectonicsand earthquake hazard in the Turkish–Iranian Plateau, *Geophys. J. Int.* **196,** 15–21.

Delavaud, E., F. Scherbaum, N. Kuehn, and T. Allen (2012). Testing the global applicability of ground-motion prediction equations for active shallow crustal regions, *Bull. Seismol. Soc. Am.***102**, 707–721.

Delavaud, E., F. Cotton, S. Akkar, F. Scherbaum, L. Danciu, C. Beauval, S. Drouet, J. Douglas, R. Basili, M. A. Sandikkaya, M. Segou, E. Faccioli, N. Theodoulidis (2012). Toward a ground-motion logic tree for probabilistic seismic hazard assessment in Europe. *Journal of seismology,* **16**, 451-473.

Douglas, J. (2004). Use of analysis of variance for the investigation of regional dependence of strong ground motions, 13 World Conference on Earthquake Engineering, Vancouver, B.C., Canada, Paper No. 29.

Douglas, J. (2011). Ground motion estimation equations 1964–2010. *Pacific Earthquake Engineering Research Center College of Engineering;* University of California, Berkeley.

Efron, B. and R. J. Tibshirani (1993). An Introduction to the Bootstrap. *Chapman & Hall/CRC*: New York.

Ghasemi, H., M. Zare, Y. Fukushima, and F. Sinaeian (2009a). Applying empirical methods in site classification, using response spectral ratio (H/V): A case study on Iranian strong motion network (ISMN), *Soil Dyn. Earthq. Eng.***29,** 111–132.

Ghasemi, H., M, Zare, Y. Fukushima, and K. Koketsu (2009b). An empirical spectral ground-motionmodel for *Iran. Journal of Seismology* **13**, 499–515.

Hessami, K. and F. Jamali (2006). Explanatory notes to the map of major active faults of Iran. *J. Seismol. Earthq. Eng.***8,** 1-11.

Idriss, I. M. (2008). An NGA empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes*, Earthq. Spectra* **24,** 217-242.

Kagan, Y. Y. and D. D. Jackson (1999). Worldwide Doublets of Large Shallow Earthquakes, *Bull. Seismol. Soc. Am.***89,** 1147-1155.

Kaklamanos, J. and L.G. Baise (2011). Model Validations and Comparisons of the Next Generation Attenuation of Ground Motions (NGA–West) Project, *Bull. Seismol. Soc. Am.***101**, 160-175.

Kaklamanos, J., L. G. Baise, and D. M. Boore (2011). Estimating Unknown Input Parameters when Implementing the NGA Ground-Motion Prediction Equations in Engineering Practice. *Earthq. Spectra***27,** 1219-1235.

Liao, Y. and J. Meneses (2012). Comparison of ground motions from the 2010 Mw 7.2 ElMayor–Cucapah earthquake with the next generationattenuation ground motion prediction equations. *Bull. Earthquake Eng.*DOI 10.1007/s10518-012-9358-7

Mai, P. M., P. Spudich, and J. Boatwright (2005). Hypocenter locations in finite-source rupture models, *Bull. Seismol. Soc. Am*. **95,** 965-980.

Massa, M., L. Luzi, F. Pacor, D. Bindi, G. Ameri (2012). Comparison between empirical predictive equations calibrated at global and national scale and Italian strong-motion data, *Bollettino di Geofisic a Teoricaed Applicata*, **53**, 37-53.

Moradi, A. S., D. Hatzfeld, and M. Tatar (2011). Microseismicity and seismotectonics of the North Tabriz fault (Iran). *Tectonophysics,***506,** 22–30.

Mousavi, M., A. Ansari, H. Zafarani, and A. Azarbakht (2012). Selection of ground motion prediction models for seismic hazard analysis in the Zagros region, Iran, *J. Earthquake Eng*. **16,** 1184-1207.

Nash, J. E., and J. V. Sutcliffe (1970). River flow forecasting throughconceptual models: Part I, a discussion of principles, *J. Hydrol.***10**, 282–290.

Nuttli OW. The excitation and attenuation of seismic crustal phases in Iran (1980). *Bull. Seismol. Soc. Am.***70**, 469–85.

Permanent Committee for Revising the Iranian Code of Practicefor Seismic Resistant Design of Buildings. Iranian code of practicefor seismic resistant design of buildings—Standard No. 2800. 2nd ed. Tehran, Iran: Building and Housing Research Center;1999.

Power, M., B. Chiou, N. Abrahamson, Y. Bozorgnia, T. Shantz, and C. Roblee (2008). An Overview of the NGA Project, *Earthq. Spectra* **24**, 3-21.

Scasserra, G., J. P. Stewart, P. Bazzurro, G. Lanzo, and F. Mollaioli (2009). A comparison of NGA ground-motion prediction equations to Italian data, *Bull. Seismol. Soc. Am.***99**, 2961–2978.

Scherbaum, F., F. Cotton, and P. Smit (2004). On the use of response spectral reference data for the selection of ground-motion models for seismic hazard analysis: The case of rock motion, *Bull. Seismol. Soc. Am*. **94**, 2164-2185.

Scherbaum, F., E. Delavaud, and C. Riggelsen (2009). Model selection in seismichazard analysis: An information-theoretic perspective, *Bull. Seismol. Soc. Am.***99**, 3234–3247.

Shoja–Taheri, J., S. Naserieh, and G. Hadi (2010). A test of the applicability of NGA models to the strong ground-motion data in the Iranian plateau, *J. Earthq. Eng.* **14**, 278-292.

Stafford, P. J., F. O. Strasser, and J. J. Bommer (2008). An evaluation of the applicability of the NGA models to ground-motion prediction in the Euro-Mediterranean region, *Bull. Earthquake Eng.***6**, 149–177.

Stewart, J. P., S. Midorikawa, R. W. Graves, K. Khodaverdi, T. Kishida, H. Miura, Y. Bozorgnia, and K. W. Campbell (2013). Implications of the Mw 9.0 Tohoku-Oki Earthquake for Ground Motion Scaling with Source, Path, and Site Parameters. *Earthq. Spectra*: **29**, S1-S21.

Trifunac, M. D., and V. W. Lee (1973). Routine computer processing of strong motion accelerograms, Earthquake Engineering Research Laboratory, Report EERL 73–03, California Institute of Technology, Pasadena, California, 1973.

Wang, D., L. Xie, N. A. Abrahamson, and S. Li (2010). Comparison of Strong Ground Motion from the Wenchuan, China, Earthquake of 12 May 2008 with the Next GenerationAttenuation (NGA) Ground-Motion Models. *Bull. Seismol. Soc. Am.***100**, 2381–2395.

Wells, D. L., and K. J. Coppersmith (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. Seismol. Soc. Am.* **84,** 974–1002.

Yaghmaei-Sabegh, S. (2012). A new method for ranking and weighting of earthquake ground-motion prediction models. *Soil Dyn. Earthq. Eng.* **39,** 78-87.

Zare, M., P. Y. Bard, and M. Ghafory-Ashtiany (1999). Site characterizations for the Iranian strong motion network, *Soil Dyn. Earthq. Eng.***18,** 101–123.

Figure Captions

Figure 1. Focal mechanisms, epicentre locations (stars) and strong-motion stations used in the current study (triangles) within 200 km of the rupture plane for the 2012 Ahar-Varzaghan dual earthquakes. Strong-motion stations that recorded the 1997 Ardebil earthquake are also shown by square symbols.The trace of the Ahar fault is also shown. Stations with generic Vs30 values are shown in gray.

Figure 2. Vs30 - distance distribution of recordings from the 2012 Ahar-Varzaghan dual earthquakes data.

Figure 3. Comparison of median prediction from the event-specific GMPE with the spectral accelerations from the 2012 Ahar-Varzaghan earthquake versus Rrup for (a) PGA, (b) T=0.5s, (c) T=1.0s, and (d) T=2.0s.

Figure 4. Dependence of intra-event residuals on Rrup for (a) PGA, (b) T=0.5s, (c) T=1.0s, and (d) T=2.0s.

Figure 5. Dependence of intra-event residuals on Vs30 for (a) PGA, (b) T=0.5s, (c) T=1.0s, and (d) T=2.0s.

Figure 6. Comparison of the standard deviations from the obtained event-specific GMPE by GA with those from the four NGA GMPEs (Mw = 6.35).

Figure 7. Comparison of median predictions of (a) PGA, (b) T=0.5s, (c) T=1.0s, and (d) T=2.0s spectral acceleration from NGA GMPEs plotted with Vs30 = 300 m/s (Left), and Vs30 = 750 m/s (Right). For comparison purposes, the median predictions of the event-specific GMPE are plotted as well.

Figure 8. Plots of intra-event residuals with respect to Rrup for PGA for the four NGA GMPEs.

Figure 9. Plots of intra-event residuals with respect to Vs30 for PGA for the four NGA GMPEs.

Figure 10. Plots of intra-event residuals with respect to periods for the four NGA GMPEs.