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How Reliable are the Ground Motion Prediction Equations?

Iztok Peruš[a] and Peter Fajfar[a]

[a] *Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova 2, Slovenia,*
e-mail: iperus@ikpir.fgg.uni-lj.si; pfajfar@ikpir.fgg.uni-lj.si

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1 ABSTRACT

Recently, several new ground motion prediction equations (GMPEs) have been developed in USA (NGA project) and elsewhere. Unfortunately, the predictions obtained by different models still differ considerably, even if a common database was used, as in the case of the NGA models. In this paper, a non-parametric approach (CAE method) has been used in order to obtain some information about the influence of different databases and different functional forms on the predictions. The results suggest that the predictions depend substantially on the selection of the effective database and on the adopted functional form. Both decisions rely to some extent on judgement. The influences of both subjective decisions are especially important at short distances from the source. The regional differences seem to be of the same or even smaller magnitude than the differences observed between different models proposed for the same region, at least at short and moderate distances. Aftershocks in the database generally decrease the median values and increase the scatter.

2 INTRODUCTION

Ground motion prediction equations (GMPEs) are used for the estimation of the ground motion parameters which are needed for the design and evaluation of important structures, including nuclear power plants (NPPs). The seismic hazard may contribute greatly to the total risk of a NPP, therefore the selection of appropriate GMPEs may have a substantial influence on the design and safety evaluation. Recently, five different groups of US researchers developed new ground motion models (AS – Abrahamson, Silva, 2008; BA – Boore, Atkinson, 2008; CB – Campbell, Bozorgnia, 2008; CY – Chiou, Youngs, 2008; and I – Idriss, 2008) within the NGA project (Earthquake Spectra, 2008). These models represent a significant advancement in the state-of-the-art in empirical ground-motion modeling. Nevertheless, in spite of starting from the same database, using advanced techniques and accounting for additional effects, quite large differences (from the engineering point of view) of the median values obtained by different models can be observed. New GMPEs have been proposed also in other parts of the world. Douglas (2008) is keeping track of the developments worldwide. Recently, there have been indications that the models developed by using regional data can be transferred to another region. Stafford et al. (2008) made comparisons of recent European (AB – Akkar, Bommer, 2007) and NGA models. Their results indicate that, for most engineering applications, the NGA models may confidently be applied within Europe. A similar conclusion was made by Campbell and Bozorgnia (2006). Douglas (2007) concluded that it is currently more defensible to use well-constrained models, possibly based on data from other regions, rather than use predicted motions from local, often poorly constrained, models. The importance of the adopted functional form, especially for the hazard at low annual probabilities important for nuclear power plants, was recently shown by Musson (2009). He demonstrated that some GMPEs may yield results, which are clearly not in accordance with commonsense, if applied for probabilistic hazard purposes. For such applications, the standard deviation related to different models is also extremely important.

The main objective of this paper is to predict the ground motion parameters by a non-parametric empirical approach, called the CAE (Conditional Average Estimator) method (Peruš et al. 2006), which does not take into account any a priori information about the phenomenon, and to compare the results with the results of recent European and NGA GMPEs. Using this approach, the influence of different databases, as well the influence of the pre-determined functional forms, used for the development of GMPEs, was investigated. The applicability of the NGA GMPEs for Europe is also discussed in the paper. The non-parametric CAE method has been already used by the authors for ground motion predictions (Fajfar and Peruš, 1997). In recent years the available ground motion databases have been greatly expanded, and especially within the NGA project, also greatly improved, compared to those available one decade ago. So, the reliability of the CAE predictions, which strongly depends on the quality of the database, has substantially increased.

3 CAE METHOD FOR GROUND MOTION PREDICTIONS

The CAE method is used for the estimation of unknown quantities (e.g. peak ground acceleration *PGA* and spectral accelerations) as a function of known data of the earthquake (e.g. magnitude *M* and fault characteristics) and of the local site (e.g. the distance measure and soil conditions). The first and the second set of variables are called the output and input variables, respectively.

In order to determine unknown output variables from known input variables, a database containing sufficient well-distributed and reliable empirical data is needed. The database should include both measured/processed values of output variables and the corresponding input variables. One particular observation which is included in the database can be described by a sample vector, which components are the input and output variables. For example, if during a magnitude M=7 strike-slip earthquake a peak ground acceleration PGA=0.34 g was recorded at a distance R=9 km, then the sample vector can be defined as $\{M, R, F; \ln PGA\} = \{7, 9, 0.5; \ln(0.34)\}$, where F=0.5 denotes the strike-slip earthquake. The database consists of a finite set of such sample vectors. According to the CAE method, the unknown output variable is determined in such a way that the computed vector composed of given and estimated data is most consistent with the sample vectors in the database. The output variables can be estimated by the formulae

$$\hat{c}_k = \sum_{n=1}^{N} A_n \cdot c_{nk}\ , \quad A_n = \frac{a_n}{\sum_{i=1}^{N} a_i} \quad \text{and} \quad a_n = \frac{1}{(2\pi)^{D/2} w_1 \cdot \ldots \cdot w_D} \exp\left[-\sum_{l=1}^{D} \frac{(b_l - b_{nl})^2}{2w_l^2} \right] \qquad (1)$$

where $\hat{c}_k$ is the k-th output variable, c_{nk} is the same output variable corresponding to the n-th vector in the database, N is the number of vectors in the database, b_{nl} is the l-th input variable of the n-th vector in the database (e.g. M or R), b_l is the l-th input variable corresponding to the vector under consideration, and D is the number of input variables. The parameter w_l is the width of Gaussian function which is called the smoothness parameter (different values of w_l correspond to different input variables). It determines how fast the influence of data in the sample space decreases with increasing distance from the point whose co-ordinates are determined by the components (input variables) of the vector under consideration. The larger the value of w_l is, the more slowly this influence decreases. Large w_l values exhibit an averaging effect. In the specific case, discussed in this paper, the natural logarithm of peak ground acceleration, ln *PGA*, was used as the only output variable. *PGA* was determined as the rotation-independent measure of horizontal ground motion (GMRotI50, defined by Boore et al., 2006) in the NGA database, and as the geometric mean in the European database. Several studies have shown that the difference between these two measures is very small.

In order to check the dispersion of the prediction, the so-called "local standard deviation" $\hat{E}_{\sigma k}$ is used, which defines the dispersion of the k-th output variable $\hat{c}_k$ determined by eqn (1)

$$\hat{E}_{\sigma k} = \sqrt{\sum_{n=1}^{N} A_n\ (\hat{c}_k - c_{nk})^2} \qquad (2)$$

$\hat{E}_{\sigma k}$ is comparable with the error estimates of ln *Y* in GMPEs. For engineering applications, the ratio between the 84th percentile and median is more informative, and is therefore used in this paper for the presentation of the dispersion of predictions. It should be noted that the results obtained by the CAE method correspond to **median values** since a logarithmic value (ln *PGA*) is used as the output variable.

The results of the CAE method depend on the choice of the values of the smoothness parameters w_l. For more details see (Peruš et al, 2006). In order to obtain reasonably smooth results, the w_l values were determined by a trial and error procedure. Constant w_M and w_{Vs30} values were used over the whole magnitude and V_{s30} range (w_M=0.4 and w_{Vs30} =200 m/s, respectively). A constant value (w_F=0.25) was used also for the style-of-faulting. In the case of the distance measure, w_R linearly decreased from $w_{R=0}$=3 km to $w_{R=100}$=13 km.

4 INPUT PARAMETERS, SCENARIO AND DATABASES USED IN THE STUDY

Almost all recent GMPEs use the ***moment magnitude***, ***distance, style-of-faulting*** and ***local site conditions*** as input parameters. Some GMPEs use also additional input parameters. In the CAE approach, it is easy to take into account any input parameter, provided that an adequate database exists. In order to enable comparisons with all NGA and recent European GMPEs, only four basic input parameters were used in our study.

Two different distance measures are used in most recent GMPEs: the closest horizontal distance to the surface projection of the rupture plane, R_{JB}, and the closest distance to the rupture plane, R_{RUP}. The relation between these two measures depends on the geometry of the fault. In this study, a vertical strike-slip fault was assumed, for which the simplest conversion between the two distance measures applies. The same scenario was used also by Abrahamson et al. (2008) and by Stafford et al. (2008). The relation between R_{JB} and R_{RUP} depends on the depth to the top of the rupture. The median values of this parameter from the NGA database were used: 6 km for M=5, 3 km for M=6, and 1 km for M=7 (Abrahamson et al., 2008). In the CAE method, a non-dimensional parameter defines the style-of-faulting. It is related to rake angle and has values from F=0.0 (normal fault) to F=1.0 (reverse fault). For a strike-slip fault F=0.5 applies. Local site conditions are characterized by the average shear-wave velocity in the top 30 m, V_{S30}. The results in this paper were obtained for V_{S30} = 520 m/s ("stiff soil" in the case of AB model). This velocity was selected considering the distribution of data and considering the range of shear-wave velocities corresponding to the "stiff-soil" in the AB model. Three NGA GMPEs include the soil/sediment depth as an additional input parameter. AS and CY models use $Z_{1.0}$ which represents the depth to V_S=1.0 km/s. The values $Z_{1.0}$=0.034 km and $Z_{1.0}$=0.024 km were used for the AS and CY model, respectively. The CB model includes $Z_{2.5}$ which represents the depth to V_S=2.5 km/s. The value $Z_{2.5}$=0.64 km was used. The used values for the soil depth are taken from Abrahamson et al. (2008) and are based on the values recommended by the original authors.

The common database, used by NGA teams, consists of 3551 publically available multi-component records from 173 shallow crustal earthquakes, ranging in magnitudes from 4.2 to 7.9. The five NGA teams used different criteria for establishing their own (effective) databases which served for the development of GMPEs. A key difference in the databases was the treatment of aftershocks. The AS and CY databases include aftershocks, resulting in a much larger number of recordings than the BA and CB databases. The Idriss database includes aftershocks, but it only includes sites with 450 m/s<V_{S30}<900 m/s. The European AB database (532 records) is considerably smaller than the databases used in NGA project. The classification of aftershocks is ambiguous. For example, the 1999 Duzce earthquake (shear-slip, M=7.12), which is included both in the NGA and in the European database, can be classified as an aftershock or as a main shock. This decision is important because inclusion of Duzce records in a database has a very substantial impact on the CAE prediction for a M=7 shear-slip earthquake. The databases used in the presented study were reconstructed based on the data available in the literature and/or by help and kind co-operation of the original authors. In addition to the European and NGA databases, new databases were formed in this study. The large database PF-L (3550 records) includes all records, which are included in any of the other bases, and the small database PF-S (927 records) includes those records which appear in all five NGA databases (if V_{S30} is in the range 450 m/s<V_{S30}<900 m/s) or in four NGA databases (all five but Idriss, if V_{S30} is outside of the range 450 m/s<V_{S30}<900 m/s). Moreover, a reduced AS (denoted as AS-M) and a reduced CY (denoted as CY-M) databases were formed by eliminating the aftershocks from the original AS and CY databases. In both cases, the Duzce records were considered as aftershocks (Abrahamson and Silva, 2008). For illustration, parts (R_{JB} <50 km) of four databases are shown in Fig 1. The records which are especially relevant for the results presented in this paper (strike-slip fault, 360m/s< $V_{s30} \leq$ 750m/s) are highlighted.

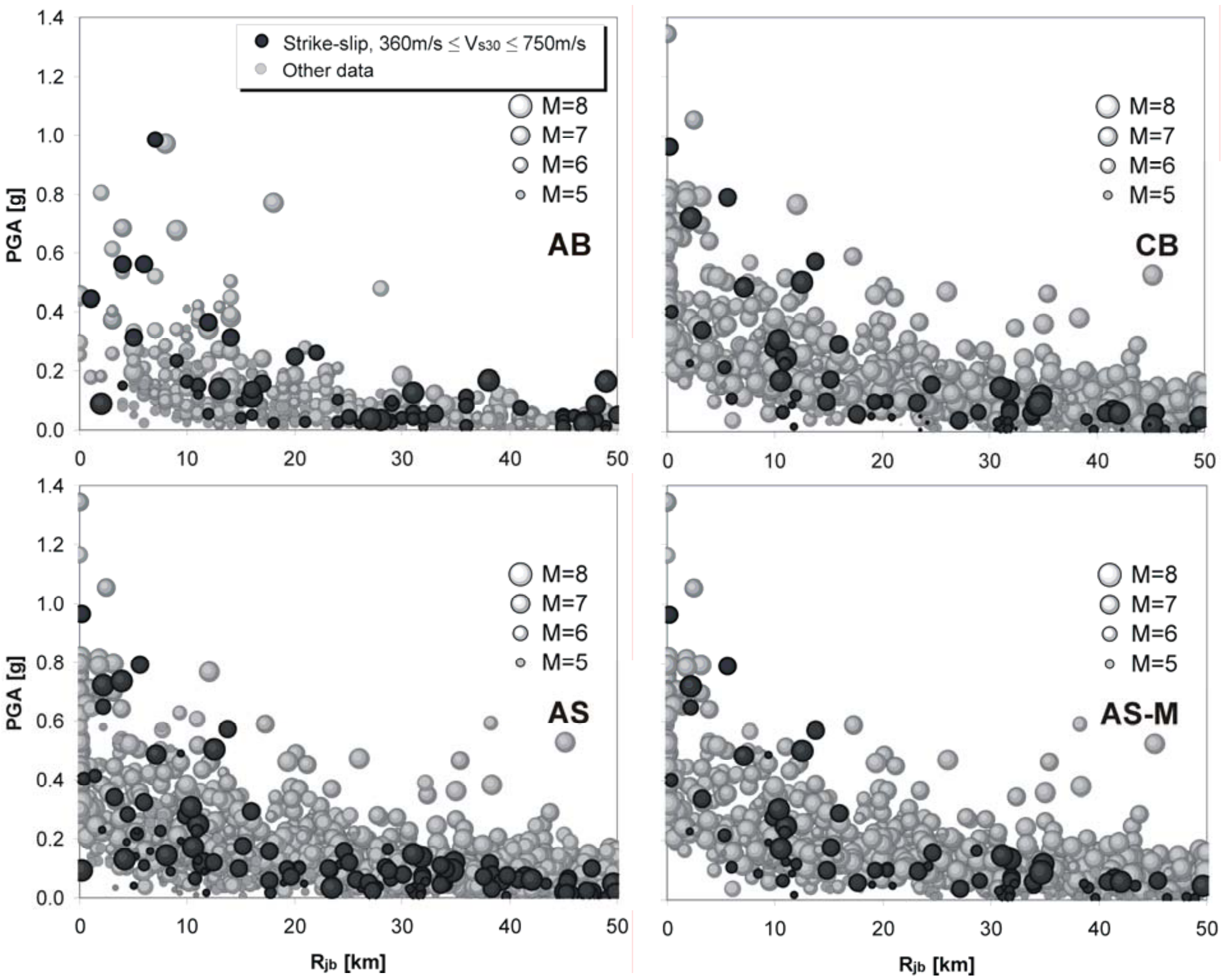

Figure 1. Data distribution for the European (AB) and three NGA databases. AS-M represents the AS database with eliminated aftershocks

5 RESULTS AND DISCUSSION

In this section the results obtained for five NGA and for one European GMPE, as well as the results of the CAE method obtained with different databases, are presented and compared. The earthquake scenario and other input data are described in Chapter 4. In the case of AS and CY models, the equation for main shocks is considered. From the engineering point of view, only strong ground motion is most important. Therefore the results are presented for the distance range 1 – 50 km. Because of space limitation, the results are presented only for peak ground acceleration *PGA* for two magnitudes (M=6 and M=7). The linear scale was used, because the logarithmic scale, generally used for the presentation of GMPEs, visually diminishes substantial differences at short distances from the source and may be thus misleading.

5.1 Comparison of GMPEs

In Fig. 2, six GMPEs are compared. Note that all the NGA GMPEs apply to main shocks, with the exception of the Idriss (I) model, which does not distinguish between main shocks and aftershocks, like the European AB model. (It is interesting to note that the AS and CY models made a distinction between main shocks and aftershocks at the very last stage of the NGA project.) The results are presented for the distance measure R_{JB} (The results for $R_{RUP,}$ which are not presented here, are very similar). A considerable difference between different NGA GMPEs can be observed. It is a result of different subsets of the common database which were used by different developing teams, and a result of different adopted functional forms. Both influences will be discussed in the continuation. The European AB model is based on a different database. It is important to note that the results of the AB model are mostly in the range of the NGA results, near to or at the lower end. The aftershocks included in the AB database may contribute to this fact. The functional form of the BA model is quite different from the form of all other models. Main differences between different

GMPEs (up to a factor of 1.5) appear at short distances. Note that differences up to a factor of 3 are reported in Abrahamson et al. (2008) for spectral values and different input data.

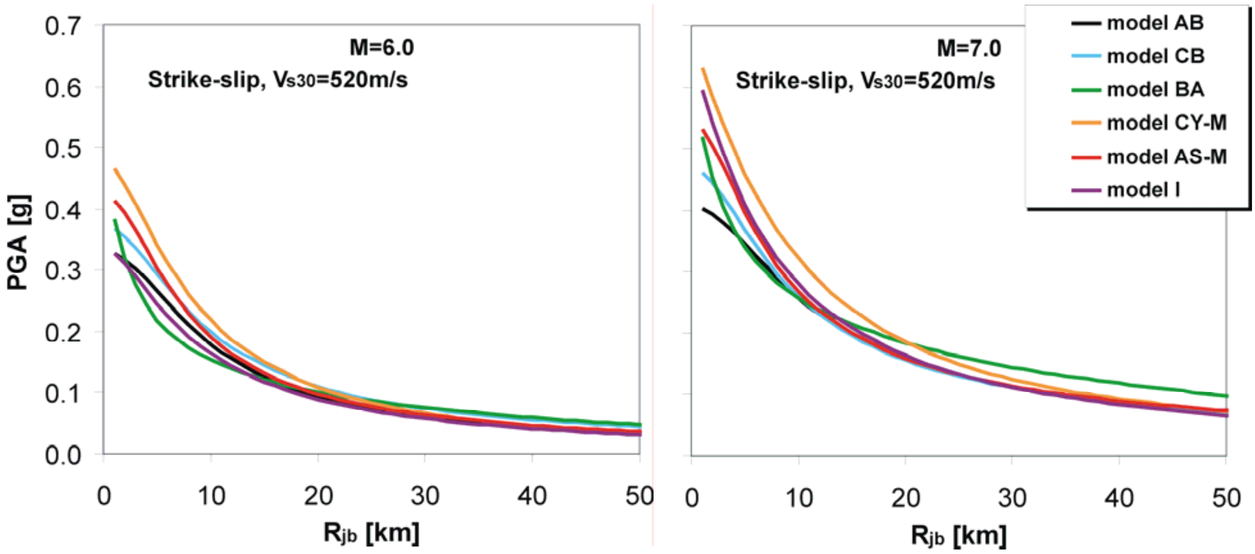

Figure 2. *PGA* as a function of R_{jb} distance for a vertical-strike slip earthquake

5.2 Influence of databases

As explained in Chapter 4, the GMPEs discussed in this paper are based on different effective databases. In order to estimate the influence of different databases, ground motion predictions were made by using the same approach, i.e. the CAE method, for all databases (CY and CY-M are not shown in Fig. 3 because the results are very similar to AS and AS-M, CY-M is shown in Fig. 4).

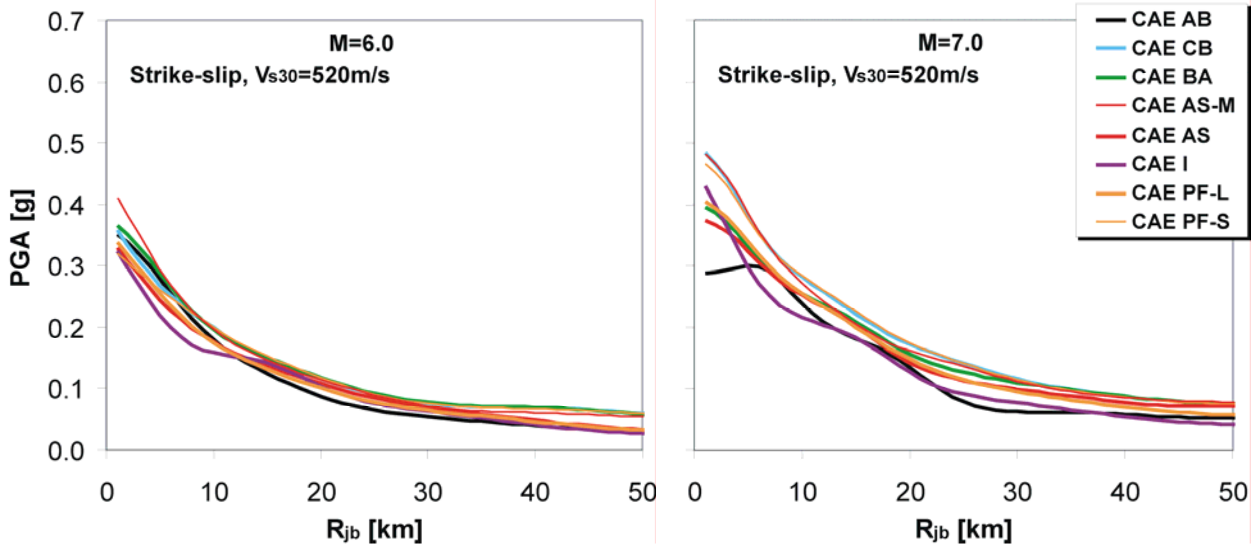

Figure 3. Comparison of *PGA* as a function of R_{jb} distance for vertical-strike slip earthquakes, obtained by CAE method for different databases

The results shown in Fig. 3 suggest that a part of differences between GMPEs shown in Fig. 2 is due to differences in databases. It can be seen that the inclusion of aftershocks diminishes the median predictions for M=6 (compare AS with aftershocks with AS-M without aftershocks, a factor of about 2 can be observed at 50 km distance). However, not all differences can be attributed to aftershocks, but also to selection of records from the common database based on different, mostly subjective criteria. The European AB database provides quite similar results as the NGA databases with aftershocks for M=6. For M=7, the difference is larger, mainly due to lack of data in this magnitude range, which does not allow a reliable CAE prediction. The lack of relevant data is especially critical at short distances, where an anomaly in the CAE prediction can be seen.

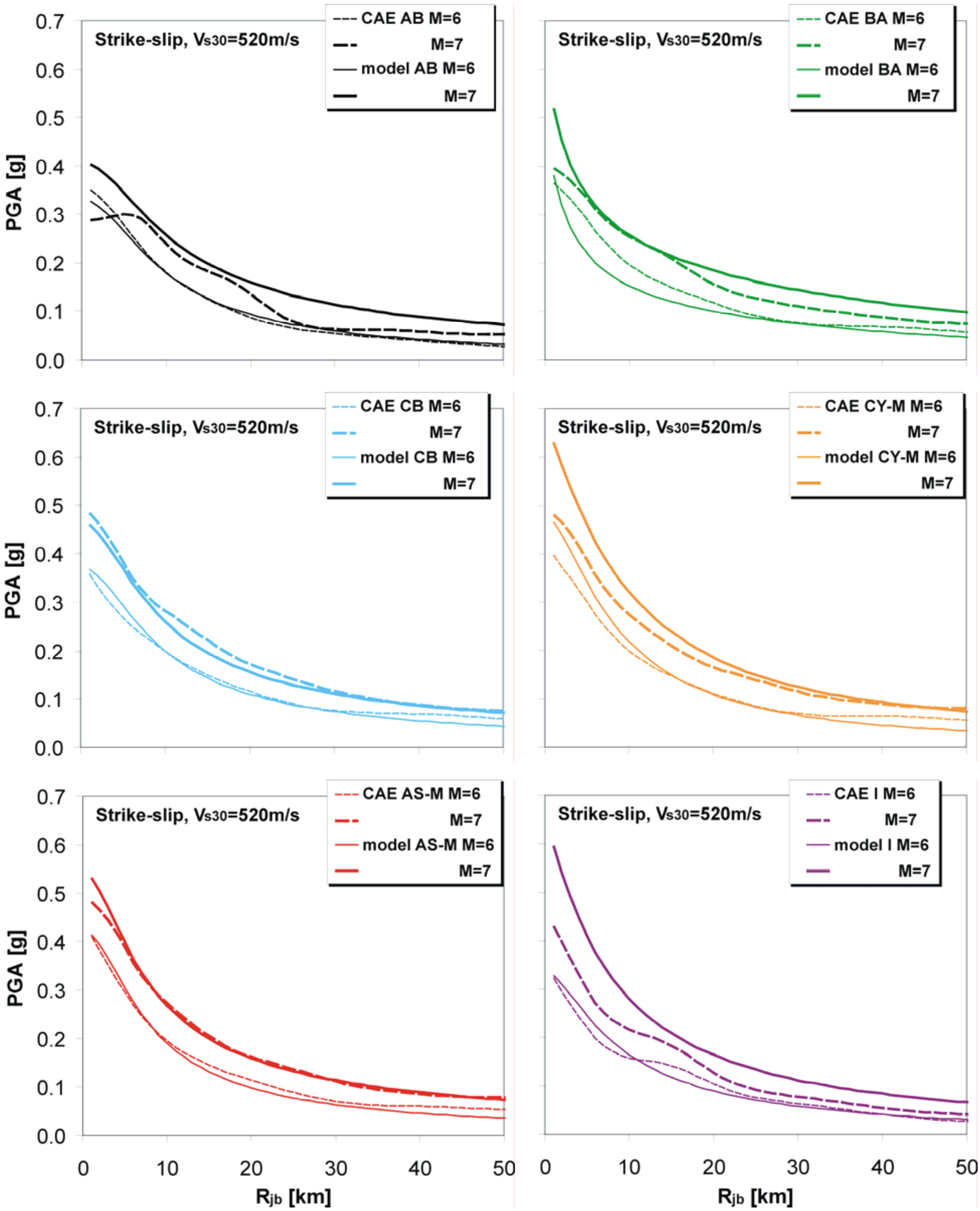

Figure 4. Comparison of *PGA* as a function of R_{jb} distance for vertical-strike slip earthquakes, obtained by CAE method and by GMPEs

5.3 Influence of the functional form

The influence of the adopted functional form can be estimated by comparing the GMPE results with the CAE results obtained for the same database as used in the development of the specific GMPE. The functional forms take into account, in addition to data, also some physical constraints and inevitably include also some judgement. The CAE results are based entirely on data, some judgement is involved only in the choice of the smoothing parameter. Comparisons are shown in Fig. 4. For M=6 the results show, generally, a reasonable agreement for all models with some exception of the BA model. For M=7, the agreement is very good in the case of the CB and AS-M models. The other models provide estimates, which are not entirely supported by data. The differences are substantial especially at short distances. The comparisons suggest that high *PGA* values at very short distances predicted by some of the GMPEs in the case of larger magnitudes may be based on the assumed functional forms. In the case of AB model the CAE prediction at very short distances are not in accordance with common sense due to the lack of relevant data.

5.4 Scatter

The ratios of the 84th and the 50th percentile (median value) of *PGA* as a function of distance are shown in Fig. 5. This ratio is used instead of standard deviation in *ln* units since it is more practical in engineering applications. The CAE results correspond to the median values shown in Fig.3. The ratios defined in the GMPEs are also shown. The CAE ratios depend on the distance and magnitude. They are somewhat smaller for M=7 than for M=6. The results suggest that the ratio (scatter) is larger for databases with included aftershocks (compare the ratio for AS with included aftershocks with AS-M). The ratio is the largest for the European AB database and the smallest is for the AS-M, CB and PF-S databases. For the larger PF-L database the ratio is considerably larger than for the smaller PF-S database.

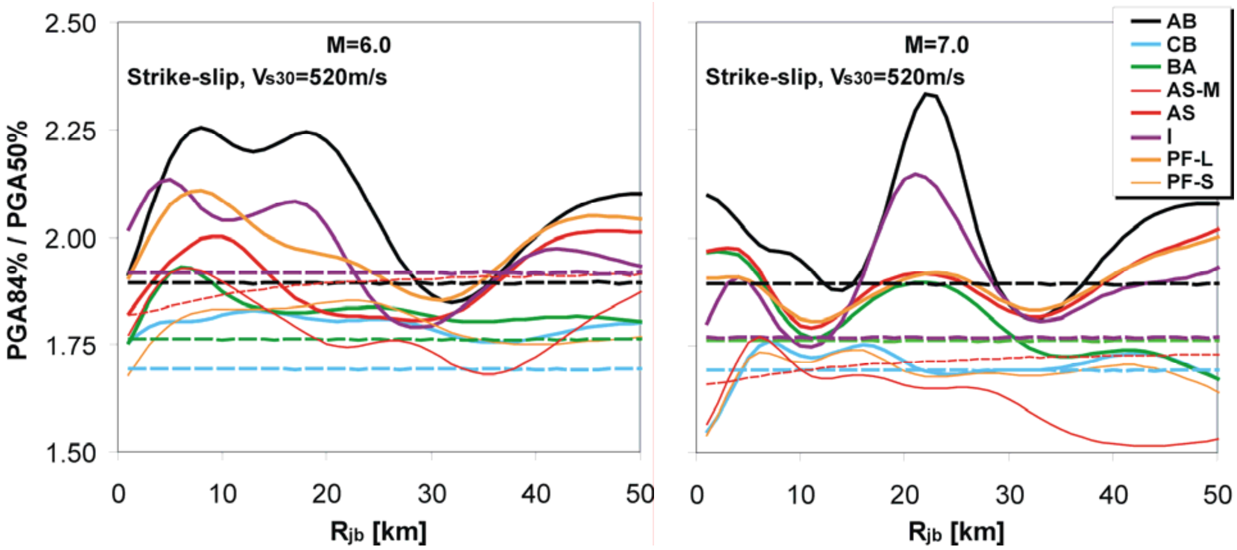

Figure 5. Comparison of the ratios of the 84th and the 50th percentile (median value) of *PGA* as a function of distance for vertical-strike slip earthquakes, obtained by GMPEs and CAE method. Dashed lines correspond to the values defined in GMPEs.

6 CONCLUSION

The aim of this study was to explore how reliable are the ground motion prediction equations. Five NGA models and one recent European model were analysed and compared with the results of the non-parametric CAE method which, in contrast to the GMPEs, does not take into account any *a priori* assumption about the phenomenon.

There are two main sources of the differences between various GMPEs. The first one is the adopted database and the second one is the assumed functional form of the GMPEs. Both rely to some extent on judgement. The five NGA teams used different subsets of the original common NGA database. The main source of differences is in the treatment of aftershocks. Those models which include aftershocks, use larger databases and generally predict smaller median values of ground motion parameters. On the other hand, the inclusion of aftershocks increases the scatter. The choice of the functional form has an important influence on the estimated ground motion, especially at short distances, where the data are scarce. The results of the study shows that all investigated models, with one exception, are in a reasonable agreement with data in the case of M=6. In the case of M=7, some model predictions are not entirely supported by data. A very good correlation can be observed in the case of the CB and AS-M models. The European AB model is based on a different database. However, the median results by the AB model are mostly in the range of the NGA results.

For the investigated scenario, the differences between the AB model and the NGA models are similar to the differences between the NGA models.

For the investigated scenario, significant differences between the predictions of different GMPEs can be observed. From the engineering point of view, a difference in a ground motion parameter of 50% represents a substantial difference in the seismic demand with important consequences for design of a structure and structural components or for the safety of an existing structure. The fact, that the NGA models differ substantially in spite of starting from the same database, suggests that the available GMPEs, although greatly improved, are not yet fully reliable, especially at short distances from the fault. On the other hand, the fact that the median results obtained by European GMPE fall in the range of the NGA predictions, suggests that the regional differences do not play a major role, at least not in the short and moderate distance range. As a consequence, the use of worldwide data in a single database seems to be feasible (as suggested by Stafford et al. 2008). Such a database should not include aftershocks, which generally decrease the median values and increase the scatter. A problem with combined databases may be the increased scatter, which can exert the dominant influence on the probabilistic seismic hazard analysis for important structures like NPPs.

The non-parametric CAE method proved to be a simple but powerful tool, especially for research. It enables quick predictions of ground motions with different databases and with different input parameters. It is easy to add to or remove data from the database and to check the influence of additional input parameters. Due to a large number of accelerographs installed worldwide, the number of records is increasing rapidly and the GMPEs may become out-of-dated in a short period of time. With increasing number of high quality data, the non-parametric approach will become more reliable and more attractive also for practical applications.

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