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PAN-EUROPEAN REPRESENTATIVE GMPE MODEL

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Abstract

Ground motion prediction equations (GMPEs) represent a key component in seismic risk analysis, and the consideration of both aleatory and epistemic sources of variability may have significant influence on the over- or under-estimation of the final assessment of losses. It has been observed that the development of new GMPEs over the past years did not improved the reduction of epistemic uncertainty, even though related knowledge is improved. A common approach to include epistemic uncertainty is to design a logic tree that proposes choices between various GMPEs with associated weights; although it is not necessarily the best suited for modelling epistemic uncertainty, as noticed by some authors. Recently, a simple and efficient model has been proposed by defining three representative GMPEs (lower, central and upper) to model epistemic uncertainty. The three GMPEs are derived from available median models. This alternative model is equivalent to the use of multiple GMPEs, provided the same range of epistemic uncertainty is sampled. The representative GMPE approach is tentatively applied to the European context for its application in risk assessment of critical infrastructures in the framework of the European-funded project INFRARISK. The resulting representative model is then confronted to actual ground motion records, which are selected from the European Strong Motion Database RESORCE. The proposed model enables a complex problem to be represented by a minimum number of branches for single-site hazard analysis and mapping.

Keywords: ground-motion model, epistemic uncertainty, seismic hazard

1. Introduction

Ground motion prediction equations (GMPEs) are recognised as a key component of any seismic risk analysis, while the consideration of both aleatory and epistemic sources of variability in the ground motion models may have significant influence on the overestimation or underestimation of the final losses. The development of new GMPEs over the past few years apparently did not contribute to decreasing epistemic uncertainty [1], even though related knowledge is improving. A common approach to include this source of epistemic uncertainty is to design a logic tree that proposes choices between various GMPEs and associated weights. This approach is not necessarily the best suited for modelling epistemic uncertainty in GMPE, e.g., [2], [3].

Recently, [4] have proposed an alternative method that consists in the definition of three representative GMPEs (lower, central and upper) in order to express the epistemic uncertainty. The three representative GMPEs are derived from existing median models, e.g., [1]. [4] show that the three-GMPE model is equivalent to the use of multiple GMPEs, provided that the same range of epistemic uncertainty is sampled. Additionally, this approach provides some advantages:

- The selection of existing GMPEs to build the representative model can be done without applying weighting coefficients, which eliminates the subjective expert-based judgement that is usually associated with the logic tree approach.
- Values are computed for discrete combinations of magnitudes and distances, thus allowing for a flexible expression of the median and the epistemic uncertainties, without requiring a given functional form.
- The three-GMPE representative model can be readily used as an input to risk analysis, because the central model and the upper/lower bounds can be sampled with appropriate weights (i.e. the relative weights are defined by the Gaussian probability density function). Because only three possible inputs are sampled, the associated computational effort is reduced when compared to a logic tree with multiple choices of GMPEs.

In the present study, the representative GMPE approach is tentatively applied to the European context for risk analysis of critical infrastructures in the framework of the European-funded project INFRARISK (http://www.infrarisk-fp7.eu/). To this end, a selection of available GMPEs based specifically on European ground-motion databases has been performed, as detailed in Section 2. Section 3 develops the steps required to derive the three-branch representative GMPE that accounts for epistemic uncertainty. The issue of the quantification of aleatory variability for the developed model is addressed in Section 4, because such knowledge is essential when using the GMPE in a probabilistic framework. Finally, the resulting three-GMPE representative model is confronted to actual ground motion records, which are selected from the European RESORCE database [5]. The performance of this Pan-European representative model can then be benchmarked with respect to individual GMPEs, by comparing the amount of records that are over- or under-estimated by the different GMPE models selected.

2. Selection of GMPEs

The most recently developed GMPEs that seek to capture epistemic uncertainty using a common database of Pan-European strong-motion records (RESORCE) were compiled in a special issue of the Bulletin of Earthquake Engineering in 2014 [6]. Four of these GMPEs are chosen as the basis for the derivation of the representative GMPE model (see Table 1), namely [7] (AK14), [8] (BI14), [9] (BO14) and [10] (DE14). These four models have all been derived by exploiting the ground-motion data from the recently developed RESORCE database [5]. This database results from the integration and uniform processing of European and Near and Middle East accelerometric archives, including some earthquake-specific studies [5]. It consists of 5,882 multi-component accelerograms from 1,814 events recorded between 1967 and 2012, making it the most up-to-date Pan-European accelerometric databank.

Table 1 – General characteristics of the selected GMPEs

Characteristics	**AK14**	**BI14**	**BO14**	**DE14**
M_w range	4.0 – 7.6	4.0 – 7.6	4.0 – 7.6	3.6 – 7.6
Distance range	0 – 200 km	0 – 300 km	0 – 200 km	1 – 547 km
Distance metric	R_{epi}, R_{hypo}, R_{jb}	R_{hypo}, R_{jb}	R_{jb}	R_{jb}
Site amplification model	$V_{s,30}$	$V_{s,30}$ or soil class	$V_{s,30}$	$V_{s,30}$
Style of faulting	Normal / Reverse	Normal / Reverse / Strike-slip / Unknown	No distinction made	Normal / Reverse / Strike-slip
Model accounting for focal depth	No	No	No	Yes
GM parameters	PGA, SA at [0.05,0.1,0.2,0.3,0.5,1.0,2.0]s, PGV	PGA, SA at [0.1,0.2,0.3,0.5,1.0,2.0]s, PGV	PGA, SA at [0.05,0.1,0.2,0.3,0.5,1.0,2.0]s	PGA, SA at [0.05,0.1,0.2,0.3,0.5,1.0,2.0]s, PGV

Based on the magnitude and distance validity domains of the underlying GMPEs, it is proposed to develop the representative GMPE model for M_w between 4.0 and 7.5, and for epicentral distances (R_{epi}) between 1 and 200 km. For models that use the Joyner-Boore distance metrics, the conversion to epicentral distance is made using the relationships given in [4], which are based on the fault model by [11]. Because the selected models directly use shear wave velocity as a proxy to soil amplification, the median $V_{s,30}$ that corresponds to each EC8 soil class is chosen to compute the averaged soil amplification factor. Regarding focal depth, the only GMPE that accounts for this parameter (i.e., DE14) uses an average depth of 10 km, justified by the vast majority of superficial earthquakes that compose the RESORCE database. Normal and strike-slip earthquakes are also by far the most common types of events that are present in the database, therefore the GMPEs that contain both of these styles of faulting (i.e., BI14 and DE14) are considered twice. Finally, in order to use all four GMPEs, only the GM parameters that are common to all of them are considered, i.e. PGA and SA at T = 0.1s, 0.2s, 0.3 s, 0.5s, 1.0s and 2.0s.

The six GMPEs are plotted in Fig. 1, for three selected magnitudes and three ground-motion parameters. They are compared to actual ground-motion records that are extracted from the RESORCE database with the following criteria: normal or strike-slip faulting style, focal depth between 0 and 20 km, $V_{s,30}$ between 360 and 800 m/s (i.e., EC8 soil class B), and M_w between 4.0 and 7.5 with +/- 0.25 magnitude bins.

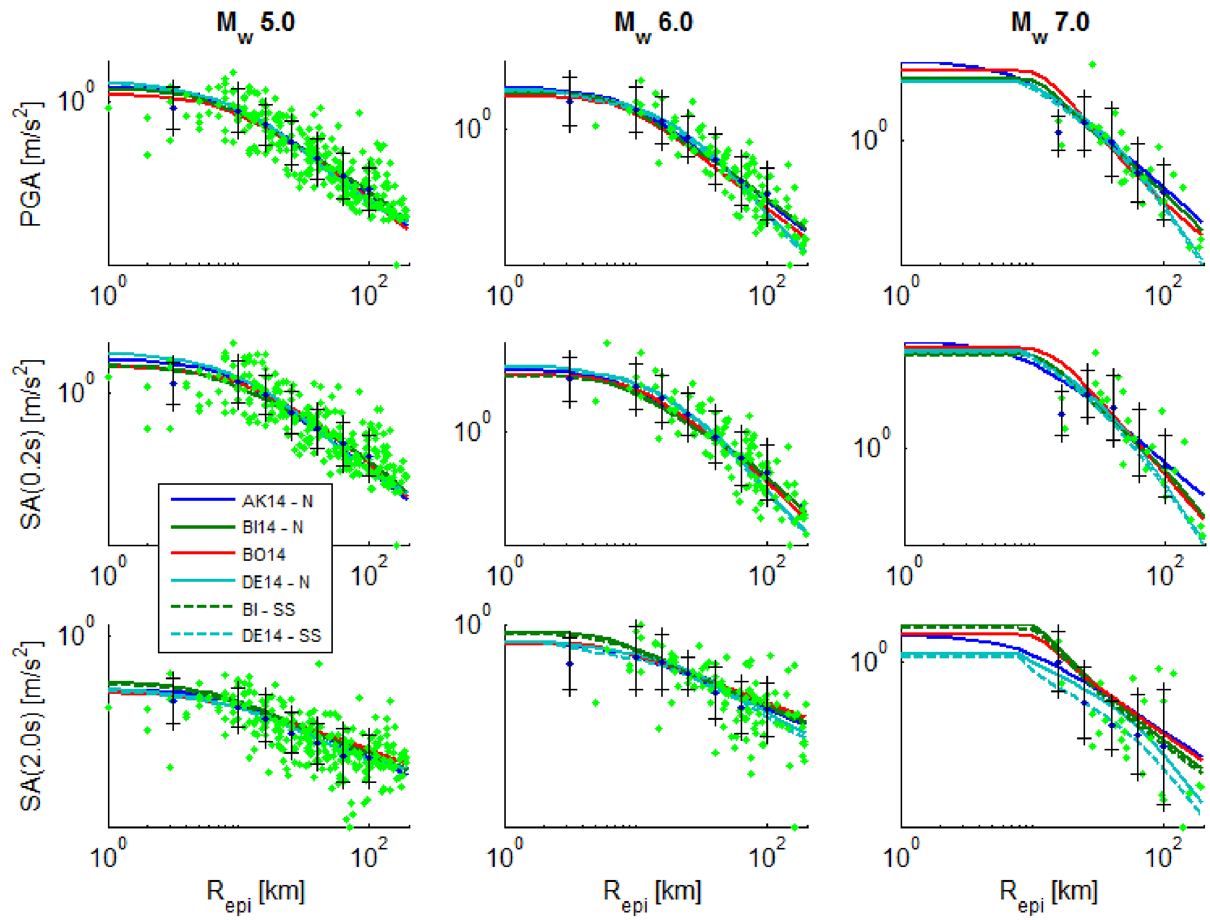

Fig. 1 – Selected GMPEs with $V_{s,30}$ = 580 m/s (N = normal, SS = strike-slip faulting). The green points represent records from the RESORCE database, while the vertical black lines correspond to the associated standard deviations over selected distance bins.

3. Development of a Pan-European representative GM model

In the present study, the proposed approach is demonstrated through the derivation of a representative GMPE for normal or strike-slip faulting and EC8 soil class B, where $V_{s,30}$ = 580 m/s is assumed to be the proxy for the corresponding amplification factor. Therefore the six models plotted in Fig. 1 are used to build the representative GMPE.

Following [4], the three-branch representative GMPE model is built as follows:

1. Selection of a set of n GMPEs that are potential candidates as ground-motion models for the area of interest (here n = 6).
2. Selection of a set of discrete magnitude and distance values, for which the representative GMPE will be generated.
3. For each combination of magnitude and distance, computation of the corresponding GM parameters $y_{1..}y_n$ from the selected GMPEs.
4. Computation of the central representative value $\overline{y}$ by processing the geometric mean: $\overline{y} = (y_1 \cdot \ldots \cdot y_n)^{1/n}$.
5. Accounting for epistemic uncertainty by using the standard deviation of the logarithms of the ground-motion parameters: $\sigma_{\log y}$ = std ($\log_{10} y_1, \ldots, \log_{10} y_n$).

6. Smoothing of the standard deviations between the discrete distances. For example, the smoothed standard deviation at distance *k* is computed as follows:

$$\sigma^{s}_{\log y,k} = 0.25 \cdot \sigma_{\log y,k-1} + 0.50 \cdot \sigma_{\log y,k} + 0.25 \cdot \sigma_{\log y,k+1} \tag{1}$$

This step enables to reduce the pinching effect of the confidence intervals if the various $y_1 \ldots y_n$ values are close to each other for some combinations of magnitude and distance.

7. Computation of the upper/lower epistemic bounds: $y_{+/-} = 10 \wedge \left(\log_{10} \overline{y} \pm \sigma^{s}_{\log y}\right)$.

8. Representation of the three-branch GMPE model in a tabulated format for various combinations of magnitude and distance, without any fitting to a functional form.

This procedure is applied to the selected European GMPEs and the corresponding three-branch representative GMPE model is represented in Fig. 2. The lower and upper bounds representing the epistemic uncertainties are estimated from the 16th and 84th percentiles (i.e. one time the standard deviation). Therefore the proposed model enables a complex problem to be represented by a minimum number of branches for single-site hazard analysis and mapping. The respective weights for the central , and upper and lower bounds could be e.g., 0.452, 0.274,and 0.274, respectively, according to the probability density function of the normal distribution.

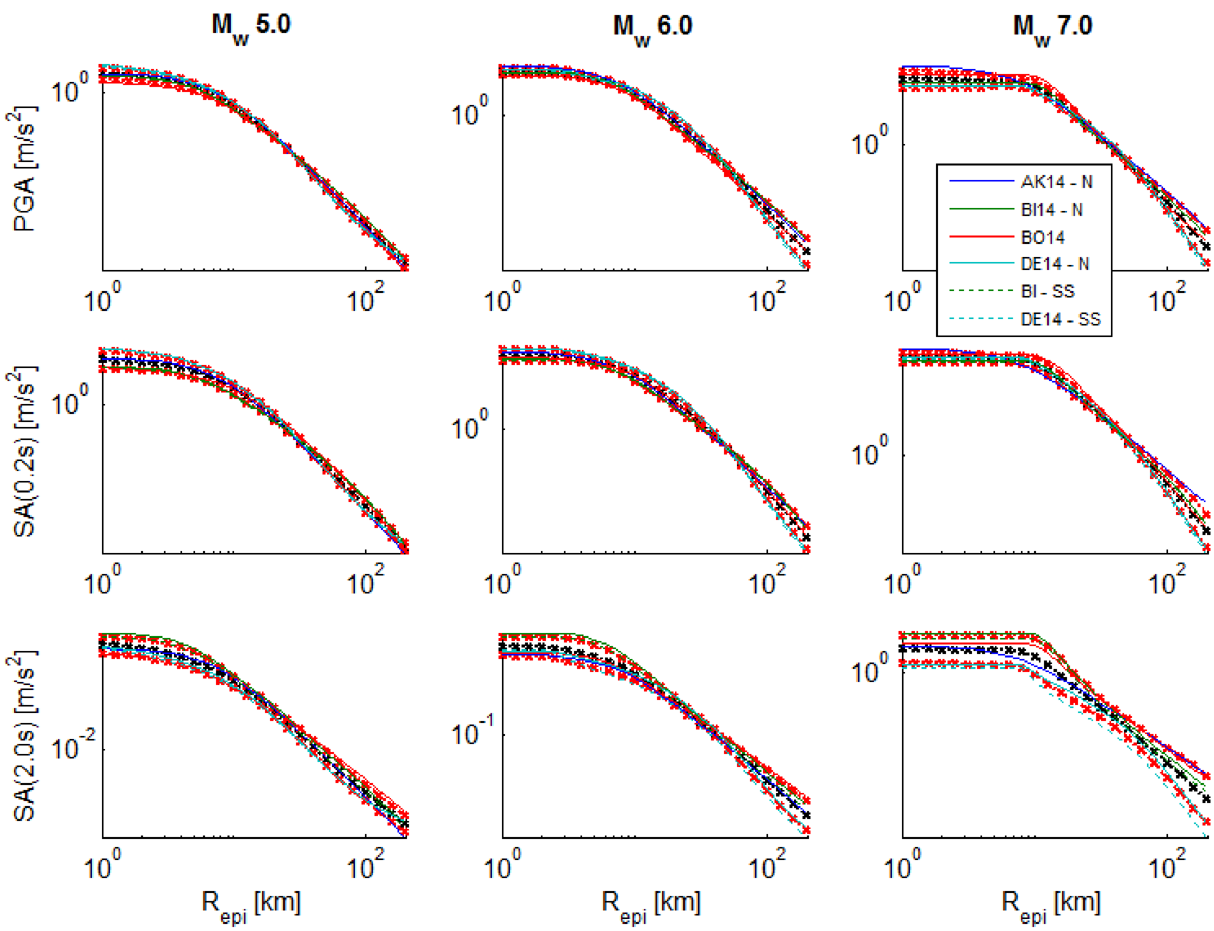

Fig. 2 – Three-branch Pan-European representative GMPE for EC8 soil class B and its underlying models. The black crosses represent the central branch and the red crosses the upper/lower bounds.

4. Aleatory variability

Once the epistemic uncertainty has been quantified for the proposed representative GMPE model, aleatory variability –represented by the intra- and inter-event terms– need to be assessed as well, in order to ensure that the model is fully characterized and usable in the context of a probabilistic seismic risk analysis.

The aleatory uncertainty can be decomposed into intra-event and inter-event variability, which are represented by the standard deviations σ_{intra} and σ_{inter}. A quadratic combination is then a common and valid approximation to express the total aleatory variability:

$$\sigma_{alea} = \sqrt{\sigma_{intra}^2 + \sigma_{inter}^2} \quad (2)$$

Similarly, the total uncertainty involved in the prediction of the ground motion parameters is expressed as follows:

$$\sigma_{tot} = \sqrt{\sigma_{epis}^2 + \sigma_{alea}^2} = \sqrt{\sigma_{epis}^2 + \sigma_{intra}^2 + \sigma_{inter}^2} \quad (3)$$

where σ_{epis} is the standard deviation representing the epistemic uncertainty that results from the choice between different GMPEs. Therefore, in order to extract the terms composing the aleatory variability, the following procedure is proposed:

1. For each combination of magnitude and distance, ground-motion parameters are computed from the selected GMPEs by randomly sampling the intra-event variability only (i.e. σ_{inter} set to 0), for a high number of outcomes (e.g. 10,000 values).
2. All the sampled outcomes enable to compute an approximation of the total standard deviation σ_{tot} (except the contribution from the inter-event variability), which is then used to extract the intra-event variability through Equation (3):

$$\sigma_{intra}^2 = \sigma_{tot}^2 - \sigma_{epis}^2 \quad (4)$$

3. The same process is applied for the inter-event variability (i.e. steps 1 and 2 with σ_{intra} set to 0), which can then be expressed as:

$$\sigma_{inter}^2 = \sigma_{tot}^2 - \sigma_{epis}^2 \quad (5)$$

4. The aleatory standard deviations are smoothed in the same way as the epistemic standard deviations, as detailed in the previous section.

This approach is motivated by the fact that the aleatory variability alone cannot be accessed through the sampling of the four original GMPEs; therefore Equation (3) is used in order to extract the intra-event and inter-event terms individually through Equations (4) and (5). As a result, the complete three-branch representative GMPE model with its aleatory confidence bounds is represented in Fig. 3 for three selected magnitudes and three ground-motion parameters. It can be noted that the aleatory part is dominating in the overall variability, especially for higher magnitude ranges, thus limiting the importance of the epistemic uncertainty due to the choice of GMPEs.

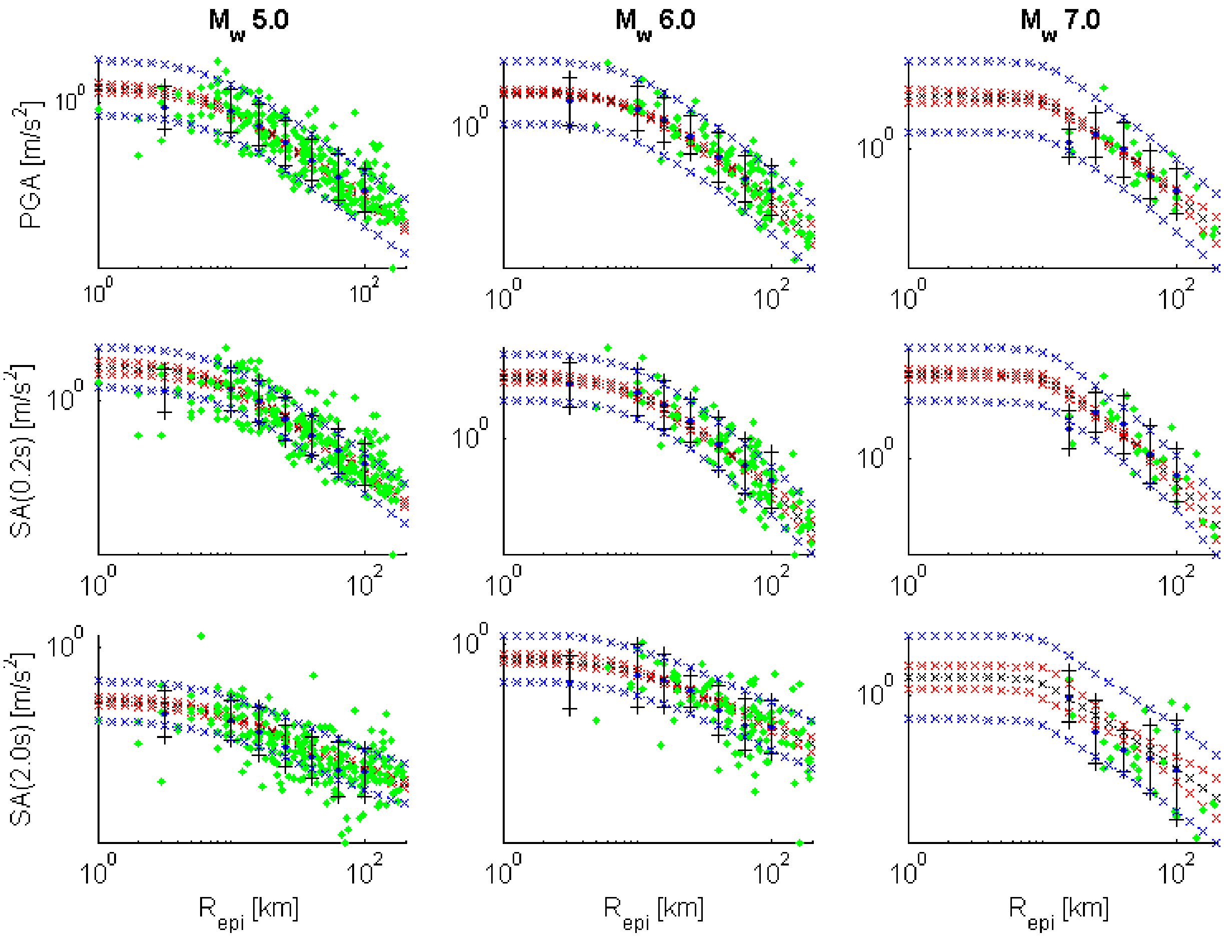

Fig. 3 – Three-branch Pan-European representative GMPE model (black and red dotted lines) with aleatory variability (blue dotted lines). Records from the RESORCE database as in Fig. 1.

[3] has showed that the distinction between epistemic and aleatory sources of uncertainty might lead to the double-counting of some epistemic uncertainties during the computation of the aleatory variability, especially when the latter is considered as the remaining variability that cannot be explained by the GMPE derivation. Therefore, [3] proposes to empirically quantify the aleatory variability by simply evaluating the average data scatter around a trend line, using the following procedure:

- Definition of some discrete distance bins (e.g. five logarithmically space bins across the 1-200km range);
- Selection of earthquake events containing a large number of relevant ground-motion records (e.g., [3] recommends at least 30 observations per event), for which a sufficient number of observations in a given distance bin is available (e.g., at least 10);
- For each event and distance bin, define a simple linear regression of the ground-motion parameter versus distance. The actual equation of this regression is not important, since the objective is not to come up with a GMPE but to set up a baseline for the computation of data scatter.
- Evaluation of the standard deviation of the residuals from the regression. This standard deviation can then be seen as the aleatory variability of the random scatter of the ground-motion parameters.

This approach has been applied to the RESORCE database; however, the density of the accelerometric data in Europe is far from that of North America used in [3]. Therefore, it was not possible to find earthquake events from RESORCE fitting the criteria recommended above . It should be noted that Atkinson (2011) has selected GMs that have been recorded on any soil class, thanks to the use of a correction factor that accounts for the site amplification. Then, only 12 RESORCE events having more than 10 observations on EC8 soil class B have been selected, as shown in Table 3.

Table 3 – Selected events for the computation of intra-event variability with the approach by [3]

EQ	Date	Mw	Nb of observations	Sigma value PGA	SA(0.2s)	SA(2.0s)
Irpinia	23/11/1980	6.9	11	0.220	0.275	0.258
- (Italy)	16/01/1981	5.2	10	0.305	0.330	0.206
Kocaeli	17/08/1999	7.6	12	0.145	0.190	0.328
Ano Liosia	07/09/1999	6.0	10	0.142	0.147	0.136
Izmit (AS)	13/09/1999	5.8	14	0.302	0.272	0.338
Izmit (AS)	11/11/1999	5.6	12	0.309	0.376	0.335
Duzce	12/11/1999	7.1	12	0.335	0.362	0.229
L'Aquila	06/04/2009	6.3	16	0.266	0.359	0.278
L'Aquila (AS)	07/04/2009	5.6	13	0.328	0.364	0.268
L'Aquila (AS)	08/04/2009	4.1	10	0.195	0.206	0.222
Gran Sasso	09/04/2009	5.4	14	0.281	0.360	0.223
Simav	19/05/2011	5.9	12	0.192	0.203	0.520

The limited number of observations per event prevents the use of distance bins, as advocated by [3] in order to obtain a more accurate regression line and to limit the effect of the non-linear decrease of the ground-motion values with respect to distance. As shown for some examples in Fig. 4, a linear trend seems to properly match the individual-event data points across the whole distance range.

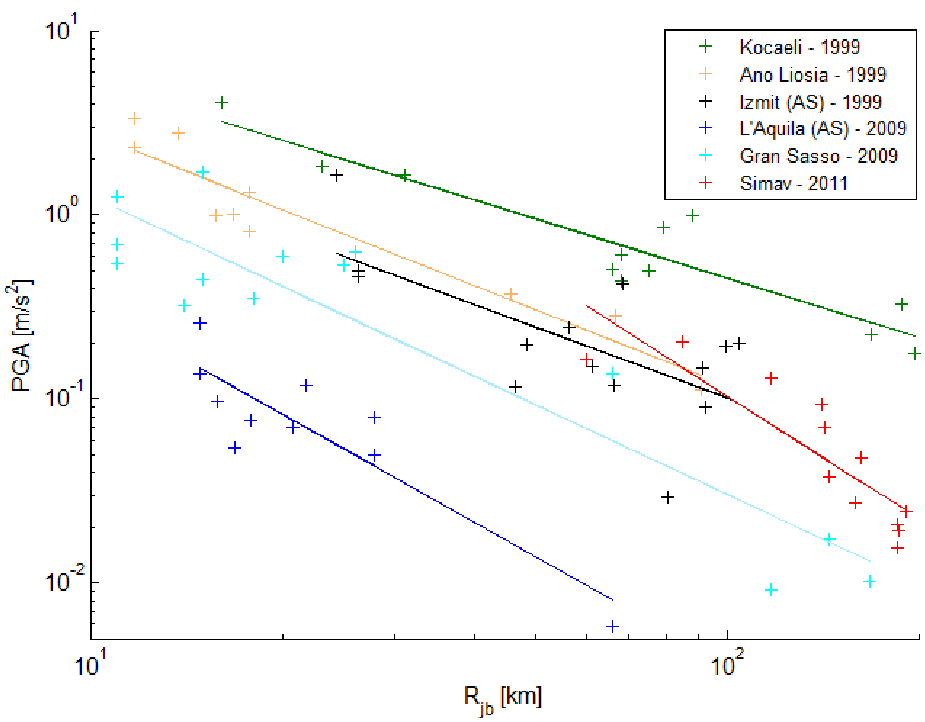

Fig. 4 – Linear fit of PGA versus distance from some earthquake events extracted from the RESORCE database

The standard deviations of the residuals for the 12 selected events are summarized in Table 3. It has been checked that they are not dependent on the magnitude or the distance range, therefore they may be averaged for each ground-motion parameter considered (see Table 4). As stated in [3], this empirically-based aleatory variability corresponds only to the intra-event term, since it is obtained from ground-motion distributions within single events. These values are compared in Table 4 with the standard deviations that have been obtained with the proposed 'sampling' approach (Equations 2 to 5). A reasonable match is achieved for the intra-event variability computed with the two methods, especially for SA at 0.2s and 2.0s, although more accurate estimates could have been obtained with better recorded events. In the case of PGA, the higher intra-event variability obtained by the 'sampling' method is mainly due to the high value of the standard deviation of one of the underlying GMPEs (BO14), which generates a high level of aleatory variability.

Table 4 – Comparison of the aleatory variability models (averaged sigmas)

Method	PGA	SA(0.2s)	SA(2.0s)
[3] (intra)	0.25	0.29	0.26
'Sampling' (intra)	0.39	0.30	0.32
'Sampling' (inter)	0.26	0.16	0.20
'Sampling' (total)	0.47	0.34	0.38

The empirical approach by [3] only provides the intra-event variability, assuming that the intra-event term corresponds to the whole aleatory component, which may only be applied if the epistemic uncertainty is defined to include the inter-event variability. This is ensured by [3] through the definition of lower and upper GMPE models that follow the lower and upper bounds of the ground-motion observations (i.e., a purely empirical procedure). In the present example applied to European GMPEs, the epistemic component is generated only by the differences between the individual GMPEs, as shown in Fig. 1, without including the inter-event variability. Therefore, it is suggested to use the aleatory variability approach that has been proposed by the 'sampling' method.

5. Validation

The potential bias of the proposed Pan-European representative GMPE model is checked by comparing the PGA predictions to the ground-motion values extracted from the RESORCE database (see Fig. 3). Eight discrete magnitude values are used in the representative GMPE model, therefore the database records are selected within M_w +/- 0:25 magnitude bins, as shown in Table 5. The geometric mean of the two horizontal components of each record is computed as the reference PGA.

Table 5 – Number of available records for each magnitude bin

Mw	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**6.5**	**7.0**	**7.5**
Records	207	265	257	174	109	56	26	12

Fig. 5 shows the proportion of RESORCE records that are found to be above or below the GMPE predictions, for each magnitude bin. Green bars represent the records that are below the median GMPE (light green for records between the median curve and the aleatory bound, dark green for records below the aleatory bound). These correspond to an overestimation of the PGA by the GMPEs. Red bars represent the records that are above the median GMPE (light red for records between the median curve and the aleatory bound, dark red for records above the aleatory bound). These correspond to an underestimation of the PGA by the GMPEs.

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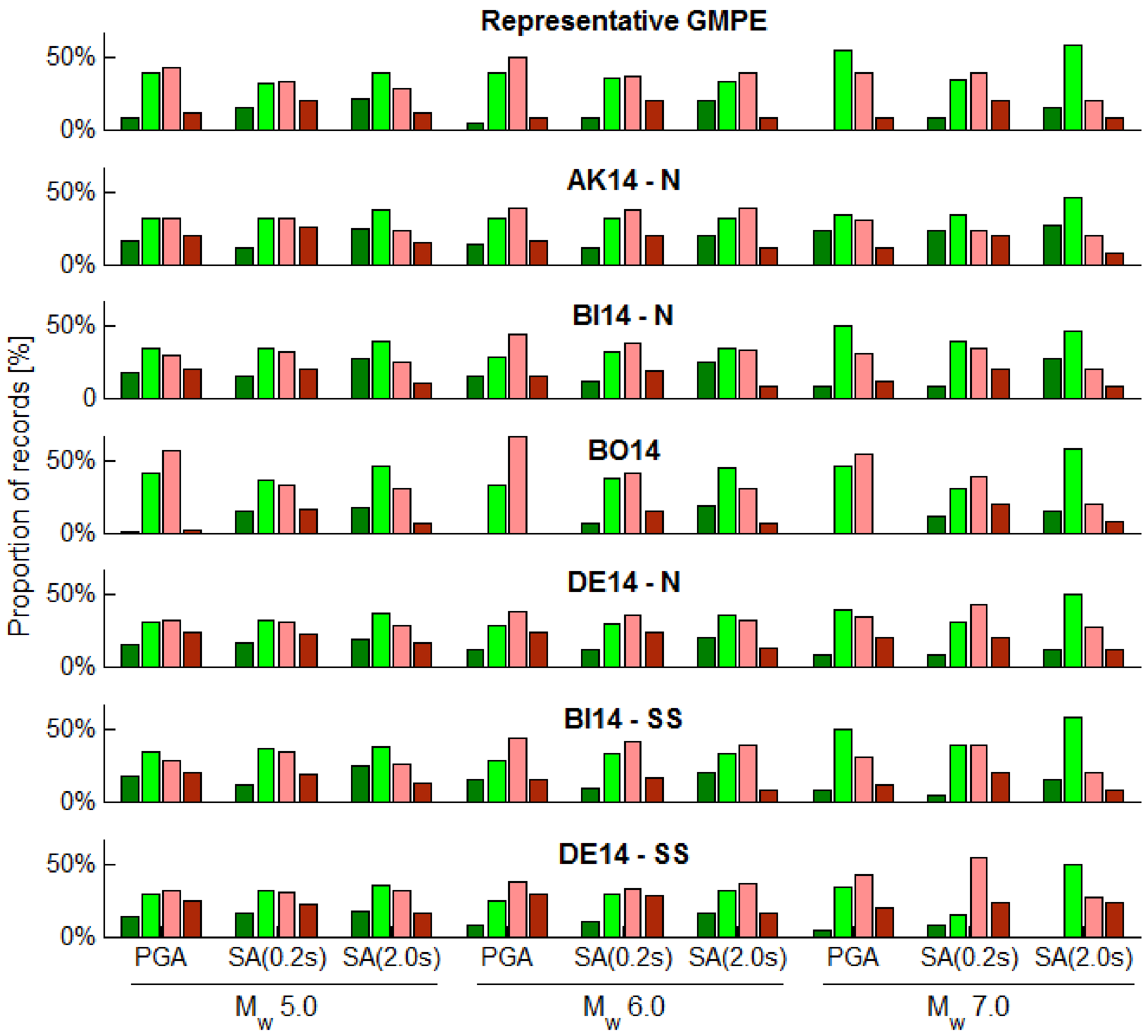

Fig. 5 – Proportion of RESORCE ground motions over- or under- predicted by the developed Pan-European representative GMPE model (top), and the individual GMPE models considered.

The Pan-European representative GMPE model seems to be more balanced than the individual GMPE models, because it combines the specific underestimations or overestimations of its underlying models. Some GMPEs (e.g., BO14) show large aleatory uncertainties, as opposed to the narrower intervals that are found for the BI14 and DE14 models. Again, the use of the representative GMPE model enables the generation of averaged uncertainty bounds. The clearest trend can be observed for M_w 5.0 and 6.0 events. These magnitude bins correspond to the largest number of records, thus ensuring a good statistical distribution of the samples. Conversely, the results become more difficult to interpret for M_w 7.0, due to the scarcity of available records. The slightly higher proportion of ground motions that are underestimated might be due to the choice of the $V_{s,30}$ value to represent the soil class (i.e., 580 m/s, the average value for EC8 soil B), while the lower bound of class B might lead to less conservative results.

Finally, it is worth noting that around 80 to 90% of the RESORCE records fall within the total uncertainty bounds (i.e. light green and light red bars), thus corresponding roughly to the definition of the +/- one standard-deviation interval within a normal distribution.

6. Conclusions

This paper has demonstrated the application to the European context of the approach originally introduced by [4] for the derivation of a three-branch representative GMPE model. Four European GMPEs, which have benefited from the recent compilation of the RESORCE ground-motion database, have been selected in order to develop a representative model for EC8 soil class B and normal or strike-slip faulting style. While epistemic uncertainty induced by the existence of multiple GMPEs is able to be properly addressed by this approach, some issues remain when quantifying the associated aleatory variability. [3] has used a fully data-driven procedure to empirically assess the aleatory variability, without double-counting uncertainty sources than may already be contained in the epistemic component. However, the relative scarcity of recorded ground-motion data in Europe prevents such empirical models to be accurately constrained. Therefore, an alternative approach has been proposed, where the aleatory terms of the underlying GMPEs are combined through a sampling process.

The comparison between the various GMPEs with respect to actual recorded ground-motion parameters is encouraging. Since the Pan-European representative GMPE model is generated for some discrete magnitude-distance combinations without using any functional form, it has the ability to smooth out the local discrepancies (e.g. overestimation or underestimation) that may appear when only a single GMPE is considered. Further developments are still required, e.g., the soil class is represented by a single $V_{s,30}$ value, while a proper sampling of all possible soil velocities within the soil class would account for the epistemic uncertainty that is induced by the representation of the site amplification. Finally, the performance of the three-branch Pan-European representative GMPE model should be tested within a probabilistic loss assessment framework, where the results could be compared to a simulation scheme using a logic tree with the four original GMPEs.

7. Acknowledgements

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