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1 **Comparisons among the five ground-motion models developed using RESORCE for the**  
2 **prediction of response spectral accelerations due to earthquakes in Europe and the Middle East**

3 John Douglas<sup>1</sup>, Sinan Akkar<sup>2</sup>, Gabriele Ameri<sup>3</sup>, Pierre-Yves Bard<sup>4</sup>, Dino Bindi<sup>5</sup>, Julian J. Bommer<sup>6</sup>,  
4 Sanjay Singh Bora<sup>7</sup>, Fabrice Cotton<sup>4</sup>, Boumédiène Derras<sup>4</sup>, Marcel Hermkes<sup>7</sup>, Nicolas Martin Kuehn<sup>7</sup>,  
5 Lucia Luzi<sup>8</sup>, Marco Massa<sup>8</sup>, Francesca Pacor<sup>8</sup>, Carsten Riggelsen<sup>7</sup>, M. Abdullah Sandikkaya<sup>2</sup>,  
6 Frank Scherbaum<sup>7</sup>, Peter J. Stafford<sup>6</sup>, Paola Traversa<sup>9</sup>

7 *Abstract*

8 This article presents comparisons among the five ground-motion models described in other articles  
9 within this special issue, in terms of data selection criteria, characteristics of the models and predicted  
10 peak ground and response spectral accelerations. Comparisons are also made with predictions from the  
11 Next Generation Attenuation (NGA) models to which the models presented here have similarities (e.g.  
12 a common master database has been used) but also differences (e.g. some models in this issue are  
13 nonparametric). As a result of the differing data selection criteria and derivation techniques the  
14 predicted median ground motions show considerable differences (up to a factor of two for certain  
15 scenarios), particularly for magnitudes and distances close to or beyond the range of the available  
16 observations. The predicted influence of style-of-faulting shows much variation among models  
17 whereas site amplification factors are more similar, with peak amplification at around 1s. These  
18 differences are greater than those among predictions from the NGA models. The models for aleatory  
19 variability ( $\sigma$ ), however, are similar and suggest that ground-motion variability from this region is  
20 slightly higher than that predicted by the NGA models, based primarily on data from California and  
21 Taiwan.

22 *Keywords:* strong-motion data; ground-motion models; ground-motion prediction equations; style of  
23 faulting; site amplification; aleatory variability; epistemic uncertainty; Europe; Middle East.

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<sup>1</sup> BRGM, Orléans, France

<sup>2</sup> Middle East Technical University, Ankara, Turkey

<sup>3</sup> FUGRO-Geoter, Auriol, France.

<sup>4</sup> ISTERre, Université Joseph Fourier, CNRS, Grenoble, France

<sup>5</sup> GFZ, Potsdam, Germany

<sup>6</sup> Imperial College London, United Kingdom

<sup>7</sup> Inst. Erd- und Umweltwissenschaften, Universitaet Potsdam, Germany

<sup>8</sup> INGV, Milan, Italy

<sup>9</sup> EDF, Aix en Provence, France

24 *1. Introduction*

25 The collection of five ground-motion models presented in other articles in this special issue has  
26 similarities to the five sets of ground-motion prediction equations (GMPEs) derived during the Next  
27 Generation Attenuation (NGA) project (Power *et al.*, 2008) and described in a special issue of  
28 Earthquake Spectra in 2008. Firstly, both sets of models were derived for state-of-the-art seismic  
29 hazard assessments for shallow active crustal seismicity in specific geographical regions: western  
30 North America (specifically California) for NGA, and Europe and the Middle East here. In passing it  
31 may be noted, however, that the NGA models have been shown to be applicable to Europe and the  
32 Middle East (Stafford *et al.*, 2008). Secondly, all five GMPEs presented here were derived based on  
33 records chosen from a common strong-motion database (RESORCE, see Akkar *et al.*, 2013c), whose  
34 compilation has similarities to the procedure followed when developing the NGA database (Chiou *et al.*,  
35 2008). Thirdly, careful data selections were made by each of the GMPE developers and state-of-  
36 the-art derivation techniques were followed. Lastly, the collection of GMPEs produced seeks to  
37 acknowledge the still considerable epistemic uncertainty present in the assessment of earthquake  
38 shaking (e.g. Douglas, 2010). For the application of the NGA models within the USGS national hazard  
39 calculations additional branches were added to the logic-tree in certain magnitude-distance bins to  
40 capture epistemic uncertainty beyond that represented by these models (Petersen *et al.*, 2008).

41 On the other hand, the collection presents significant differences with respect to the NGA models.  
42 Firstly, unlike the NGA models, which were all derived using regression analysis, generally the  
43 random-effects approach (e.g. Abrahamson and Youngs, 1992), (although with some coefficients fixed  
44 *a priori* based on physical arguments), here only two models were derived in this way (Akkar *et al.*,  
45 2013a, b; Bindi *et al.*, 2013). Two of the others are non-parametric models derived using data-driven  
46 approaches (Derras *et al.*, 2013; Hermkes *et al.*, 2013) and the other model (Bora *et al.*, 2013) makes  
47 predictions of response spectral accelerations using random-vibration theory based on empirical  
48 models for Fourier amplitude spectra and durations. Secondly, unlike the multi-year NGA project,  
49 which involved extensive interactions among developers and other project participants (leading to  
50 multiple iterations of the models), the models presented here were derived in a much shorter period  
51 and following limited communication among groups. Although the development of RESORCE was  
52 funded by SHARE and SIGMA, which led to some interactions among the model developers, this  
53 special issue is principally the fruit of parallel and independent efforts (by authors in five countries)  
54 rather than a coordinated national project. This means that the differences in the approaches used are  
55 larger than for NGA. It is possible that the use of multiple approaches for the models presented in this  
56 volume more effectively captures epistemic uncertainty in terms of the centre, the body and the range  
57 of technically-defensible interpretations of the available data (USNRC, 2012). Thirdly, the  
58 independent parameters used by the models presented here are: common among groups (all use only:

59 moment magnitude,  $M_w$ ; distance to the surface projection of the fault,  $R_{JB}$ <sup>10</sup>; the same style-of-  
60 faulting classifications; and the average shear-wave velocity to 30m,  $V_{S30}$ ) and fewer (e.g. data were  
61 insufficient to include terms involving sediment depth,  $Z_{1.0}$  or  $Z_{2.5}$ , or depth to the top of rupture,  $Z_{TOR}$ )  
62 than in the NGA models. This makes comparisons among the models and their use in future seismic  
63 hazard assessments easier since no adjustments for differences in independent parameters (e.g.  
64 Bommer *et al.*, 2005) are required. Lastly, no strict model requirements were agreed at the beginning  
65 of the derivation procedure, unlike those imposed on the NGA model developers, which means that  
66 the models presented here have varying ranges of applicability in terms of, for example, magnitude  
67 and distance.

68

69 Despite the differences between the NGA project and this special issue, the NGA comparison article  
70 by Abrahamson *et al.* (2008) is used as a template for this article comparing the five models presented  
71 in this issue, namely those by: Akkar *et al.* (2013a, b) (their model using  $R_{JB}$ ), Bindi *et al.* (2013) (their  
72 model using  $V_{S30}$  directly<sup>11</sup>), Bora *et al.* (2013), Derras *et al.* (2013) and Hermkes *et al.* (2013). This  
73 decision means that comparisons between the figures presented here can be readily made to those  
74 shown in Abrahamson *et al.* (2008) because the same choices of independent parameters and the same  
75 axes and scales are used (also to help in making these comparisons the same figure numbering has  
76 been retained). Note that some of the graphs show predictions up to  $M_w$  8, for consistency with  
77 Abrahamson *et al.* (2008), even though some developers do not recommend their models are applied  
78 for such large earthquakes (Table 1). To further facilitate comparisons with the NGA models,  
79 predictions from the GMPEs of Boore and Atkinson (2008) are included on the figures. This NGA  
80 model was chosen from among the five because it is the most similar to those presented in this special  
81 issue through its use of  $R_{JB}$  and fewer independent variables, e.g. no terms using  $Z_{TOR}$  or  $Z_{1.0}$  (or  $Z_{2.5}$ )  
82 are included. Because the models presented here have fewer independent parameters and the aleatory  
83 variabilities (standard deviations) of the models are all homoscedastic (uniform for all independent  
84 and dependent variables) some figures drawn by Abrahamson *et al.* (2008) are not relevant and are not  
85 drawn. They are replaced with figures showing other features of the models that are not covered by the  
86 other graphs, for example the influence of style of faulting on ground-motion predictions (e.g.  
87 Bommer *et al.*, 2003).

88

89 The next section presents the data selection criteria used by the different groups. The following  
90 sections compare different aspects of the models in terms of: attenuation with distance, scaling with

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<sup>10</sup> Akkar *et al.* (2013a, b) also derived GMPEs using epicentral ( $R_{epi}$ ) and hypocentral ( $R_{hyp}$ ) distances. These are not considered in this article.

<sup>11</sup> Bindi *et al.* (2013) also derived GMPEs using hypocentral ( $R_{hyp}$ ) distance and EC8 site classes rather than  $V_{S30}$  directly. These models are not considered in this article.

91 magnitude, style-of-faulting factors, site amplification, predicted response spectra and aleatory  
92 variability. The article ends with some brief conclusions.

## 93 2. Data selection criteria

94 All GMPE developers started with the same RESORCE archive, which is presented by Akkar et al.  
95 (2013a) in this special issue. At the time of model derivation this databank contained 5,882 mainly-  
96 triaxial accelerograms (from  $0 \leq R \leq 587 \text{ km}$ ) from 1,814 earthquakes (with  $2.8 \leq M_w \leq 7.8$ ) and 1,540  
97 different strong-motion stations. The five groups of developers applied different selection and  
98 exclusion criteria, which led to them using between only 14% and 38% of the available accelerograms  
99 (see Table 1). The same magnitude ranges were used by all groups, except by Derras *et al.* (2013) who  
100 used a slightly lower minimum magnitude (3.6 rather than 4.0), to select their data and only Bindi *et*  
101 *al.* (2013) and Derras *et al.* (2013) varied from the distance cut-off of 200km (using 300km and  
102 547km, respectively, instead). None of the RESORCE developers used selection criteria based on  
103 earthquake type (e.g. mainshock, aftershock or swarm) or considered its influence on ground motions.  
104 Consequently all types of earthquakes (including aftershocks) were selected, unlike Boore and  
105 Atkinson (2008) who exclude this type of event when deriving their NGA model and other NGA  
106 models that included terms in their models to distinguish between mainshocks and aftershocks. As  
107 discussed by Douglas and Halldorsson (2010) there is considerable doubt over the classification of  
108 European earthquakes into mainshock, aftershock and swarm and their analysis using the data and  
109 model of Ambraseys et al. (2005) suggested that the influence of earthquake type on ground motions  
110 is limited. A similar conclusion is reached by Bindi et al. (2013) after examining the residuals for their  
111 model separated into mainshock and aftershock classes. The five model databases principally  
112 comprise records from normal and strike-slip earthquakes, with a smaller number of accelerograms  
113 from reverse-faulting events. The distribution of records by style-of-faulting is reasonably uniform  
114 with respect to magnitude but the largest ( $M_w > 7$ ) earthquakes are mainly from strike-slip earthquakes  
115 in Turkey (Kocaeli and Düzce) and Iran (Manjil). The variation in the final databases principally  
116 results from the exclusion of data based on the filters used to process the accelerograms. The result of  
117 these various selection criteria are different sizes of databases used for the derivations of the five  
118 models (Table 1). All of the models were derived using roughly 1 000 strong-motion records.

119 One major difference between the data used by the models compared here and that used for the NGA  
120 models is the large number of poorly-recorded earthquakes. This is indicated by the mean number of  
121 records per earthquake for the five RESORCE models being between 3.0 and 5.8 (Table 1) whereas  
122 the mean number of records per earthquake for the NGA models varies between 13.1 and 27.1. This  
123 difference implies that the terms of the models related to the earthquake source (e.g. style-of-faulting  
124 terms and between-event standard deviations) are more poorly constrained than they are in the NGA  
125 models, which, as shown below, leads to significant differences in these aspects of the models. The

126 complexity of the source modelling in some of the NGA models, however, means that these models  
127 may suffer from trade-offs, for example between the effect of  $Z_{TOR}$  and style-of-faulting.

### 128 3. Attenuation with distance

129 The decay with distance from the source for peak ground acceleration (PGA) and spectral acceleration  
130 for a structural period of 1s and 5% critical damping [SA(1s)] can be seen in Figure 1, for  
131  $V_{S30}=760\text{m/s}$ , i.e. NEHRP B/C boundary (Building Seismic Safety Council, 2009) (soft rock,  
132 Eurocode 8 class B), and in Figure 2, for  $V_{S30}=270\text{m/s}$ , i.e. NEHRP D (soft soil, Eurocode 8 class C).  
133 Generally the decay rates are similar as are the predicted ground motions, particularly for small and  
134 moderate events and PGA. Predictions from the models derived by standard regression techniques  
135 (Akkar *et al.*, 2013a, b; Bindi *et al.*, 2013) are comparable except at the limits of their applicability  
136 ( $M_w$  8 and close to the source of large earthquakes,  $R_{JB}<10\text{km}$ ). Bindi *et al.* (2013) include an anelastic  
137 attenuation<sup>12</sup> term for short periods whereas Akkar *et al.* (2013a, b) tried including such a term but  
138 found that it converged to a non-physical value and hence they removed it from their functional form.  
139 Predictions from the nonparametric models show considerable variations and the model of Hermkes *et al.*  
140 (2013) shows a complex decay rate, with a change of slope (often flattening) starting around 50km.  
141 Despite all models having being derived from a common original archive (even if the final databases  
142 used differed), a factor of two difference in predicted median ground motions from the models is not  
143 uncommon, except for magnitudes and distance near the centre of the available data (e.g.  $M_w$  6).

144 As is becoming commonly recognised and modelled, the decay of earthquake ground motions is  
145 magnitude dependent. This effect can be seen by comparing the decay rates for  $M_w$  5 (roughly  $1/R^{1.5}$   
146 for PGA) to those for  $M_w$  8 (slower than  $1/R$ ). The predicted ground motions from the RESORCE  
147 models all decay more rapidly than those from the GMPEs of Boore and Atkinson (2008), particularly  
148 for PGA, which leads to much lower predicted ground motions at moderate distances (roughly 20-  
149 100km) from these models compared to Boore and Atkinson (2008). Boore and Atkinson (2008) note  
150 that their distance dependence for small earthquakes and long periods may be biased towards a decay  
151 that is less rapid than the true decay. The faster decay of ground motions in Italy (from where a  
152 considerable portion of the data used to develop the RESORCE models comes) than in California was  
153 previously noted by Scasserra *et al.* (2009).

### 154 4. Magnitude scaling

155 The magnitude scaling of the five models show the expected behaviour of higher scaling at long  
156 structural periods (Figure 3). All models show nonlinear magnitude scaling with, generally, lower

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<sup>12</sup> The expression ‘anelastic attenuation’ is only strictly valid for GMPEs for Fourier amplitudes and not response spectral ordinates.

157 dependence of ground motions on magnitude for large events. This nonlinear behaviour is expected  
158 from physical models (e.g. Douglas and Jousset, 2011). Some studies (e.g. Schmedes and Archuleta,  
159 2008) provide physical arguments for oversaturation of short-period ground motions for large  
160 earthquakes (i.e. ground motions that decrease as magnitude increases). This effect is not seen for any  
161 of the final RESORCE models for magnitudes within their range of applicability. However, when  
162 Akkar *et al.* (2013a, b) included a cubic magnitude term they found that the obtained model predicted  
163 oversaturation for  $M_w > 7.25$ , which they considered physically unrealistic and hence they finally  
164 adopted a functional form that did not allow such oversaturation. They note, however, that due to a  
165 lack of data from large earthquakes in Europe and the Middle East there is considerable epistemic  
166 uncertainty in magnitude scaling for  $M_w > 7.5$  and hence they suggest including additional branches in a  
167 logic tree to account for this uncertainty. As for the distance decay, within the magnitude range that is  
168 well covered by data ( $M_w$  5 to 7) the models predict similar spectral accelerations whereas for larger  
169 earthquakes the models differ greatly, depending on whether they are solely driven by the data or the  
170 functional form assumed. The magnitude scaling of the RESORCE models is broadly in line with that  
171 predicted by the Boore and Atkinson (2008) GMPEs, although because of the lower attenuation  
172 predicted by this model there is a considerable offset in the predictions at the considered distance of  
173 30km.

#### 174 5. Style-of-faulting factors

175 The effect of style of faulting (faulting mechanism) on strong ground motion was highlighted by the  
176 review of Bommer *et al.* (2003), who compared predictions of the reverse-to-strike-slip spectral ratios  
177 ( $F_{R,SS}$ ) for various GMPEs (their Figure 3) and who also discussed the limited number of estimates of  
178 the ratio of normal-to-strike-slip motions ( $F_{N,SS}$ ) then available. In the decade since then many more  
179 estimates of these factors have been published as part of GMPEs, including in the NGA models, but  
180 they still show considerable dispersion. Nevertheless, as shown by the example of the Boore and  
181 Atkinson (2008) ratios plotted on Figure 4, reverse-faulting events are often thought to generate  
182 slightly higher amplitude motions than strike-slip earthquakes that in turn are slightly higher than  
183 motions from normal-faulting earthquakes.

184 Figure 4 compares  $F_{R,SS}$  and  $F_{N,SS}$  for the five RESORCE models [and those of Boore and Atkinson  
185 (2008)]. All developers, except Hermkes *et al.* (2013), assumed ratios that are independent of  
186 magnitude and distance. Using a nonparametric approach Hermkes *et al.* (2013) find ratios that depend  
187 weakly on these variables. These ratios are generally quite close to unity (i.e. rupture mechanism has  
188 no effect on spectral accelerations) but two models (Bindi *et al.*, 2013; Hermkes *et al.*, 2013) show  
189 large values for  $F_{R,SS}$  ( $>1.25$ ), particularly those of Hermkes *et al.* (2013), whose ratios reach over two.  
190  $F_{N,SS}$  are generally within 0.1 of unity except, again, for Hermkes *et al.* (2013) at moderate and long  
191 periods where the ratios reach 1.5. The overall observation that the style of faulting has a limited

192 impact on spectral accelerations is in line with the findings from previous studies, including those  
193 associated with the NGA models. The usual order of which style of faulting leads to the highest and  
194 lowest motions is reversed in the model of Derras *et al.* (2013), which predicts that normal-faulting  
195 events cause higher SAs than reverse-faulting earthquakes. One possible reason for this is that only 93  
196 of the 1,088 records used to derive this model are from reverse-faulting events (compared to 540 from  
197 normal and 455 from strike-slip earthquakes) and, in addition, each earthquake is only associated with  
198 on average 3.4 records (Table 1) and hence the style-of-faulting factors are poorly constrained. In view  
199 of this, the style-of-faulting factors implied by the model of Derras *et al.* (2013) are not recommended  
200 for application. Compared with the NGA database, RESORCE is much richer in data from normal-  
201 faulting earthquakes, e.g. less than 3% of the records used by Boore and Atkinson (2008) come from  
202 normal events, and consequently the estimates of  $F_{N,SS}$  from the RESORCE models are much better  
203 constrained.

#### 204 6. *Scaling with $V_{S30}$*

205 All models (Figure 5) predict an overall inverse dependence on  $V_{S30}$ , i.e. as  $V_{S30}$  increases ground  
206 motions decrease, even if no functional form was imposed. In addition, the models predict a stronger  
207 dependence on  $V_{S30}$  for longer structural periods (Figure 5, Figure 6). All of the models except those  
208 of Bindi *et al.* (2013) and Bora *et al.* (2013) include nonlinear site behaviour, i.e. lower amplifications  
209 on soft soils (low  $V_{S30}$ ) for stronger shaking (Figure 5, Figure 6). However, once again the dispersion  
210 in the predictions is quite large, particularly at longer periods.

211 The ratios of spectral accelerations on soft soil to rock reach their peak for a structural period of  
212 around 1s with ratios of three or even higher (up to about 5.5 for Hermkes *et al.*, 2013) (Figure 6),  
213 although they show considerable variation among models. Similarly the peak in the stiff-soil-to-rock  
214 ratios is at about 1s but the peak ratios are lower (around 1.5) and show smaller dispersion. These  
215 ratios are similar to those represented in a similar plot (their Figure 10) by Ambraseys *et al.* (2005).  
216 One difference with the NGA models, however, is that the peak amplification occurs in the NGA  
217 models at a longer period ( $>3s$ ) [see, e.g., the curves for Boore and Atkinson (2008) in Figure 6],  
218 which could be related to soil profiles that are deeper on average in California than in Europe and the  
219 Middle East (Stewart *et al.*, 2012) or to smaller sedimentary basins in Europe compared to California  
220 that give rise to 2D-3D basin effects at shorter periods. Also the long-period site amplifications  
221 predicted by the Boore and Atkinson (2008) model are generally lower than those predicted by the  
222 RESORCE models.

#### 223 7. *Predicted response spectra*

224 The models all predict similar response spectra on NEHRP B/C boundary sites for  $M_w$  5 to 7 at  
225  $R_{JB}=10km$  (Figure 7); any differences in the models become apparent at large magnitudes, longer

226 distances and for softer sites (see, e.g., Figures 1 and 2). For the largest events, the functional forms  
227 used to develop the models of Akkar *et al.* (2013a, b), Bindi *et al.* (2013), Bora *et al.* (2013) and  
228 Hermkes *et al.* (2013) allow evaluation up to  $M_w$  8 whereas the model of ( Derras *et al.* (2013) should  
229 not be used for such magnitudes. The periods of the plateaus in the spectra do not show strong  
230 magnitude dependency. Predictions from the GMPEs of Boore and Atkinson (2008) at this distance  
231 for all magnitudes fall roughly in the middle of the predictions from the RESORCE models but  
232 because of the lower attenuation predicted by this model the predicted spectra for longer distances are  
233 higher than those predicted by the RESORCE models (not shown here).

234 The predicted spectra for soft soil sites show a much broader plateau and greater dispersion than in the  
235 predicted spectra on rock (Figure 8), which is due to the strong long-period site amplifications  
236 predicted by some models (Figure 6). Again a factor of two in the predicted spectral accelerations can  
237 be seen between the highest and lowest predictions.

#### 238 8. Aleatory variability

239 As noted above, all models predict homoscedastic aleatory variability (standard deviation, sigma) and  
240 consequently only a single figure is required to summarise this aspect of the models (Figure 9). As  
241 Akkar *et al.* (2013a, b) note there is limited data from larger earthquakes and consequently the  
242 apparent magnitude dependency seen within their between-event residuals may not represent the true  
243 aleatory variability at large magnitudes. Consequently they assumed magnitude-independent sigmas.  
244 Similar arguments hold for the other models. The sigmas fall into two groups: Bora *et al.* (2013),  
245 which has slightly higher values, and the other four models. This difference is related to higher values  
246 of the between-event (tau) standard deviations whilst the within-event (phi) standard deviations are  
247 similar. The sigmas show similar dependence on period with a first peak between 0.1 and 0.2s (near  
248 the plateau of predicted response spectra) and then a further increase in sigma as period increases.  
249 However, the period dependency is quite limited with less than a 20% difference between the lowest  
250 and the highest sigma.

251 The values of tau for the models of Akkar *et al.* (2013a, b), Derras *et al.* (2013) and Hermkes *et al.*  
252 (2013) are similar to those of the NGA models although slightly higher [see, e.g., the curve for Boore  
253 and Atkinson (2008) shown on Figure 9], whereas the taus of Bindi *et al.* (2013) and Bora *et al.* (2013)  
254 are larger. The values of phi of the different models are slightly (by about 0.1 ln units for moderate  
255 magnitudes) higher than those of the NGA models [again, see the curve for Boore and Atkinson  
256 (2008) on Figure 9], which leads to overall sigmas that are also about 0.1 ln units higher. The NGA  
257 models of aleatory variability also do not show a strong period dependence. The higher estimates of  
258 aleatory variability for the RESORCE models compared with the sigmas of the NGA models could be  
259 related to: a) truly higher variability in ground-motion databases in Europe and the Middle East  
260 (caused by, e.g., mixing together of data from a wide geographical region with different tectonics and

261 geology); b) the use of more data from small earthquakes whose motions are possibly intrinsically  
262 more variable than those from large events because of, e.g., higher variability in stress drops; or c)  
263 problems with the metadata in RESORCE, particularly for small events (or more likely a mixture of  
264 these reasons). (Insufficiently complex functional forms for the RESORCE models cannot explain this  
265 difference because it is apparent even for the non-parametric models). One aspect of the metadata that  
266 could be revisited in future models for Europe and the Middle East, particularly for applications below  
267  $M_w$  5.5, is the use of moment magnitude (sometimes obtained by conversions from other magnitude  
268 scales) rather than local magnitude ( $M_L$ ) for the smaller earthquakes. It was shown by Bindi *et al.*  
269 (2007), for north-western Turkey, that the use of  $M_L$  for small earthquakes leads to lower estimates of  
270 between-event variability ( $\tau$ ) compared to using  $M_w$ . This is because corner frequencies for such  
271 earthquakes are generally higher than 1Hz, which is the frequency range at which  $M_L$  is measured  
272 whereas  $M_w$  is measuring energy at frequencies below the corner and hence it is a poorer measure of  
273 the size of such events. Therefore, it could be envisaged that  $M_L$  is used below, say,  $M_w$  5.5 for the  
274 derivation of GMPEs and then in applications the local magnitude scale for that region is used to  
275 evaluate the model. Sabetta and Pugliese (1987) adopted a similar composite magnitude scale ( $M_L$   
276 below  $M$  5.5 and surface-wave magnitude,  $M_s$ , above this limit) when deriving their GMPEs for Italy.

## 277 9. Conclusions

278 In this article, various aspects of the five ground-motion models that are described in other articles in  
279 this special issue have been compared. Despite all the developers having started with the same  
280 common strong-motion archive and having used the same independent parameters, the predicted  
281 spectral accelerations from the models show significant differences, which can be related to varying  
282 data selection criteria and derivation techniques. All aspects of the models for the median ground  
283 motions (magnitude scaling, style-of-faulting factors, distance decay and site amplification) show  
284 variation from one model to the next. These differences when combined lead to variations in the  
285 predicted response spectral accelerations for scenarios of interest of more than a factor of two. These  
286 differences demonstrate that epistemic uncertainty in ground-motion prediction in Europe and the  
287 Middle East remains large and it cannot be explained by differences in the metadata of the strong-  
288 motion records used or different sets of independent parameters (e.g. hypocentral distance rather than  
289 Joyner-Boore distance or surface-wave magnitude rather than moment magnitude). One of the reasons  
290 for this large epistemic uncertainty is that a given earthquake in Europe and the Middle East is, on  
291 average, recorded by fewer strong-motion instruments than in California, Taiwan and Japan and hence  
292 the aspects of the models related to source effects are less well constrained.

293 The aleatory variabilities are slightly higher than those associated with the NGA models, again (e.g.  
294 Strasser *et al.*, 2009) showing that this aspect of ground-motion modelling is stable within a narrow  
295 band ( $\pm 0.2$  ln units) around 0.7 (for PGA). In particular, estimates of the within-event variability ( $\phi$ )

296 show little variation from one study to the next. The between-event variability ( $\tau$ ), however, can be  
297 significantly affected by the inclusion of data from smaller (less well-studied) earthquakes. Further  
298 studies to constrain the value of  $\tau$  for European events are, therefore, recommended.

299 The five models presented in this volume should be of considerable value for seismic hazard  
300 assessments in Europe and the Middle East, providing both state-of-the-art predictions of spectral  
301 accelerations and a basis for quantifying epistemic uncertainty in those predictions.

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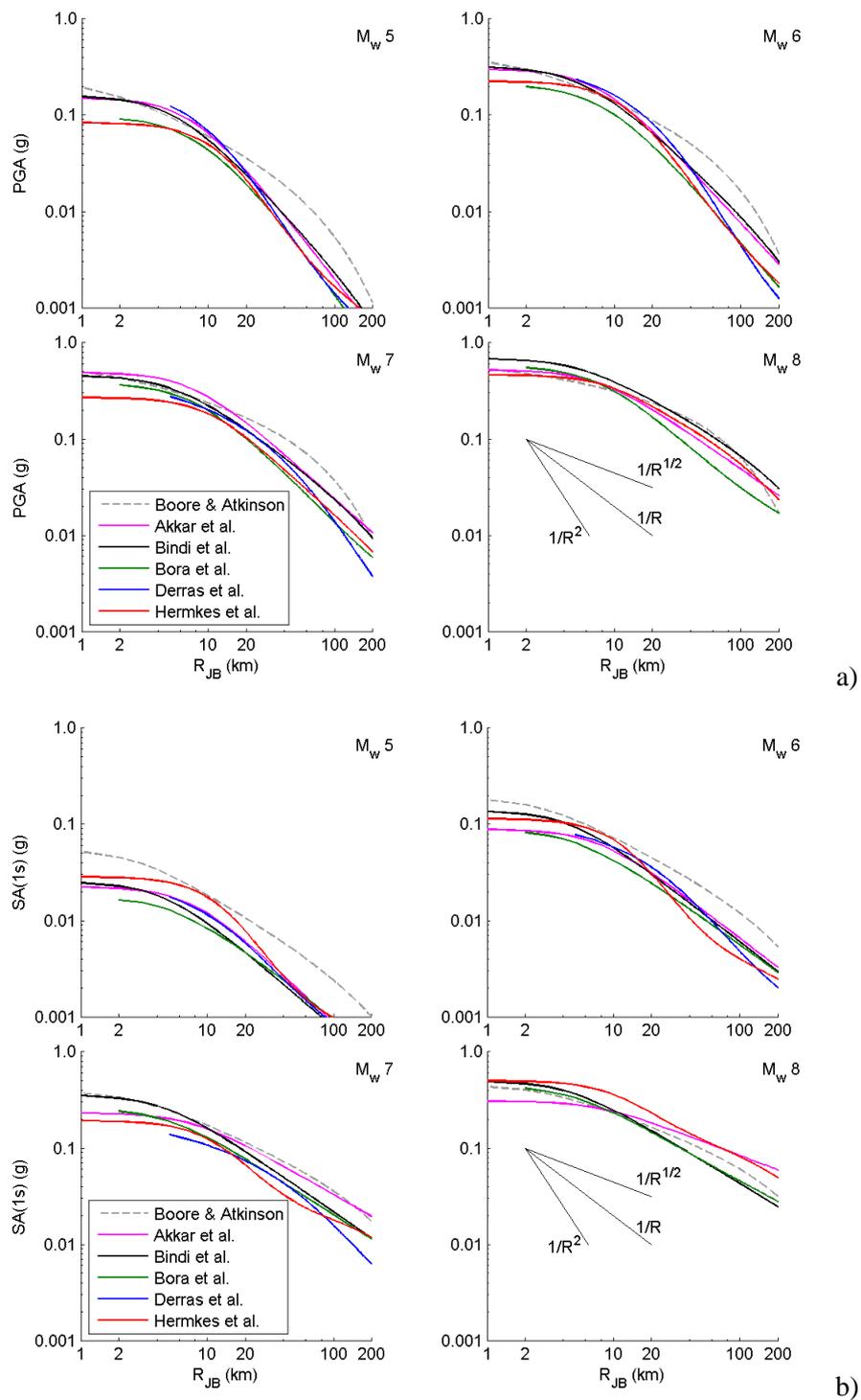
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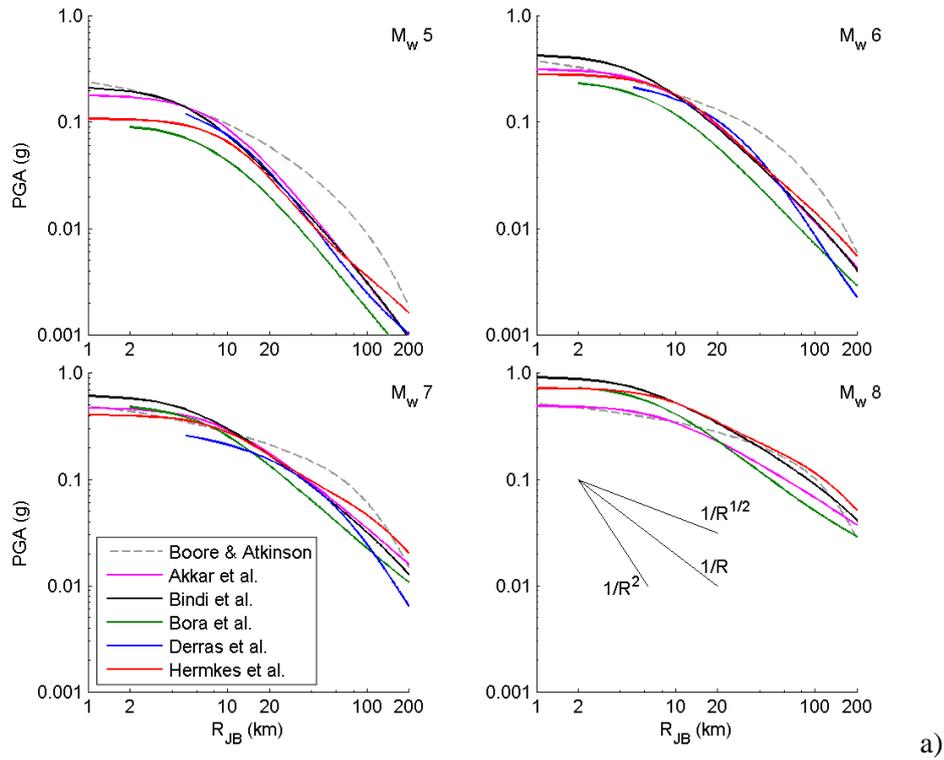


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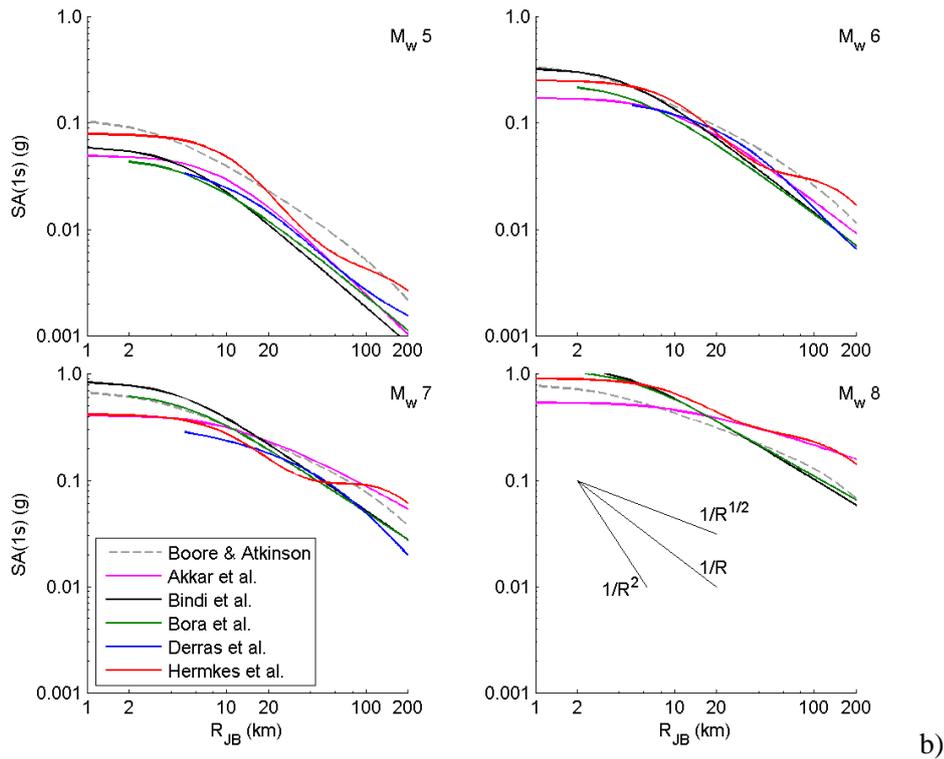
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395 *Figure 1: Comparison of distance scaling for strike-slip earthquakes for  $V_{S30}=760$  m/s (NEHRP B/C*  
 396 *boundary) for  $M_w$  5 (top left), 6 (top right), 7 (bottom left) and 8 (bottom right) for a) PGA and b)*  
 397 *SA(1s). The predictions from the model of Derras et al. (2013) are not shown for  $M_w$ 8 since this is*  
 398 *outside its range of applicability. The other models are shown for this magnitude even though some*  
 399 *developers do not recommend their application for such large events.*

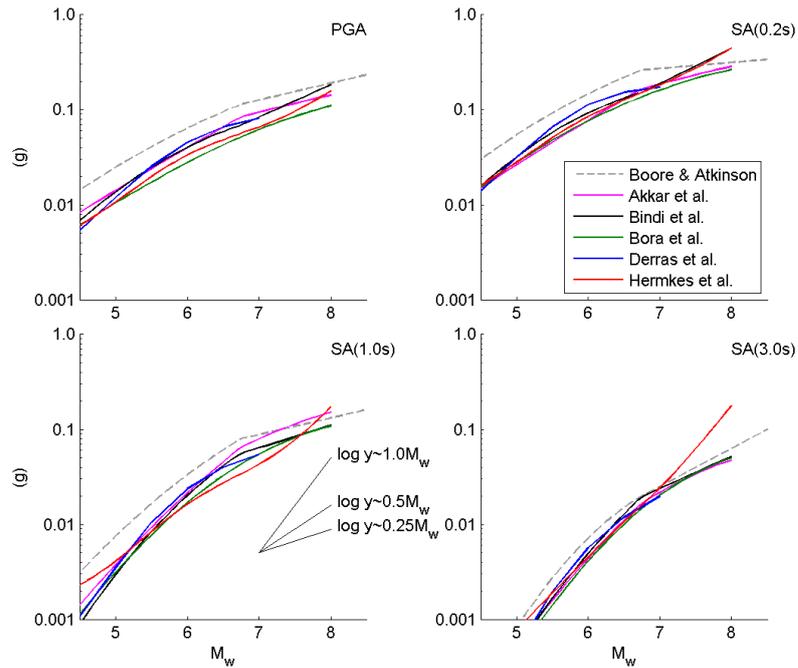
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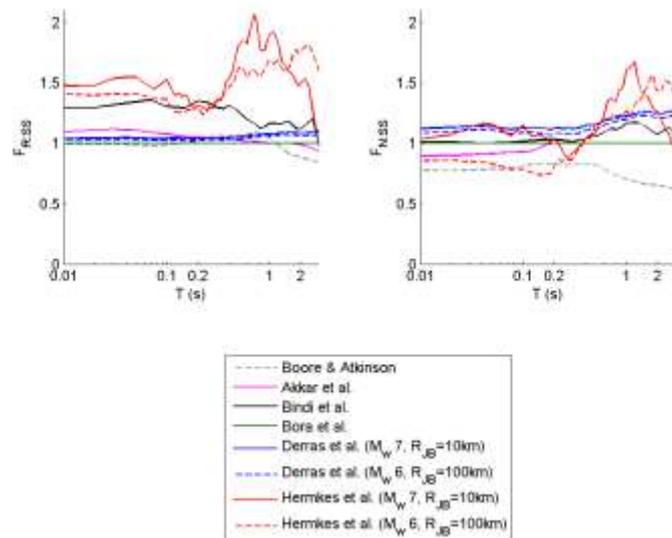


402 *Figure 2: Comparison of distance scaling for strike-slip earthquakes for  $V_{S30}=270$  m/s (NEHRP D) for*  
 403  *$M_w$  5 (top left), 6 (top right), 7 (bottom left) and 8 (bottom right) for a) PGA and b) SA(1s). The*  
 404 *predictions from the model of Derras et al. (2013) are not shown for  $M_w$ 8 since this is outside its*  
 405 *range of applicability. The other models are shown for this magnitude even though some developers*  
 406 *do not recommend their application for such large events.*



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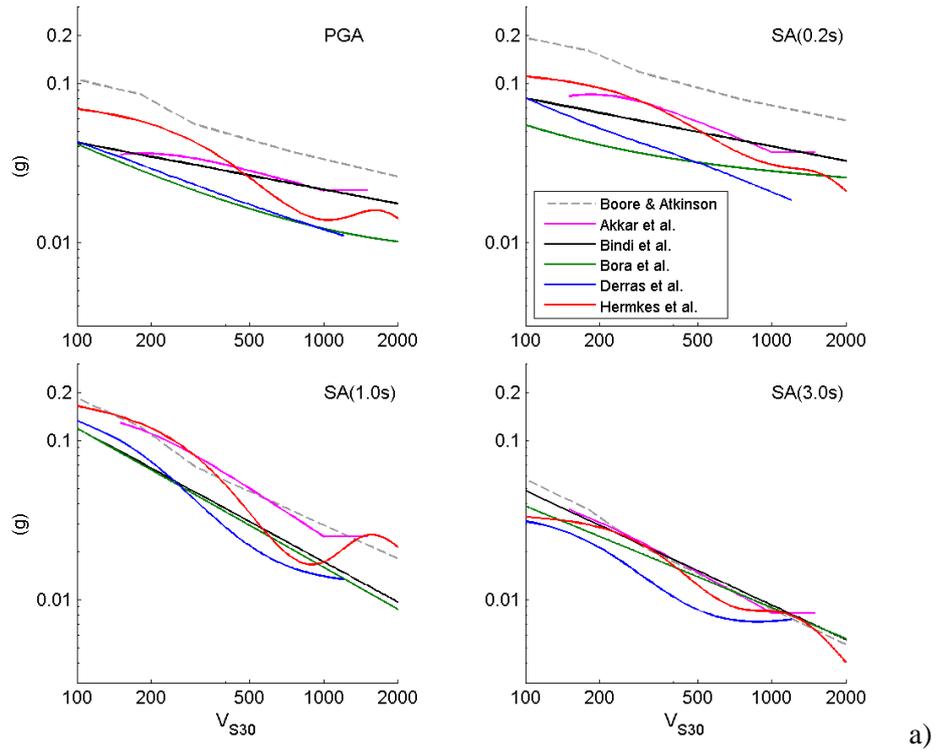
408 *Figure 3: Comparison of magnitude scaling of the median ground motion for strike-slip earthquakes*  
 409 *and  $V_{S30}=760$  m/s (NEHRP B/C boundary) at  $R_{JB}=30$  km for PGA (top left), SA(0.2s) (top right),*  
 410 *SA(1.0s) (bottom left) and SA(3.0s) (bottom right). Predictions are generally shown up to  $M_w$  8 even*  
 411 *though some developers do not recommend their models for such large events.*



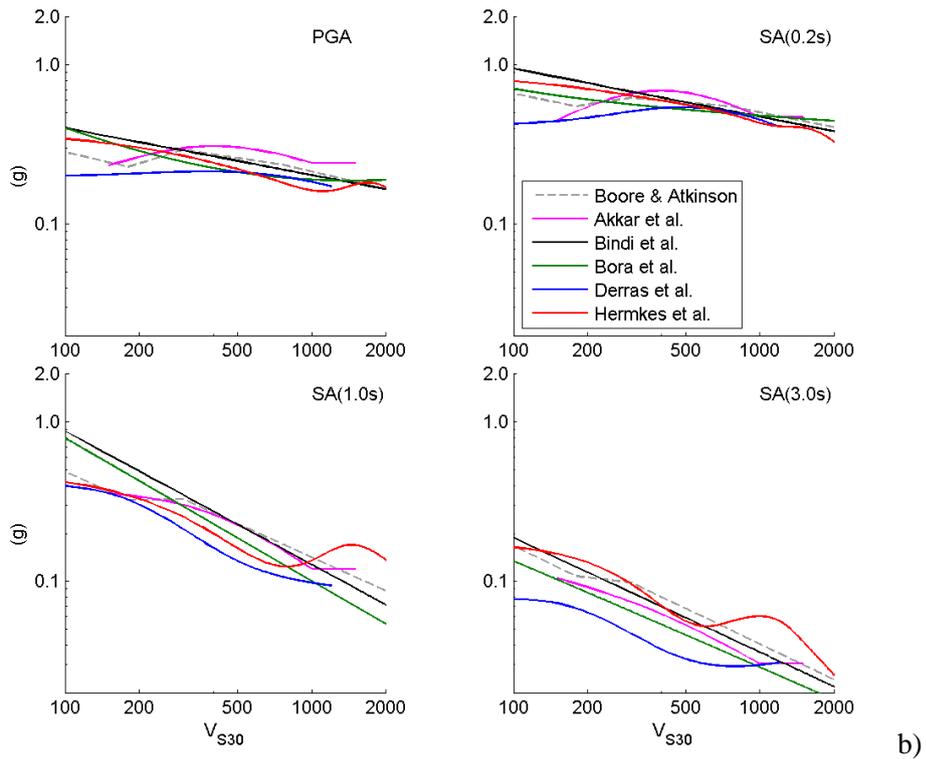
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413 *Figure 4: Comparison of style-of-faulting factors for SA: a) ratio of reverse to strike-slip ( $F_{R,SS}$ ) and b)*  
 414 *ratio of normal to strike-slip ( $F_{N,SS}$ ). Ratios are scenario-independent except for those of Hermkes et*  
 415 *al. (2013). The predictions of Bora et al. (2013) are independent of the style of faulting.  $F_{N,SS}$  of Akkar*  
 416 *et al. equals unity for  $T>0.2$ s and therefore this curve is under that of Bora et al. (2013) for these*  
 417 *periods.*

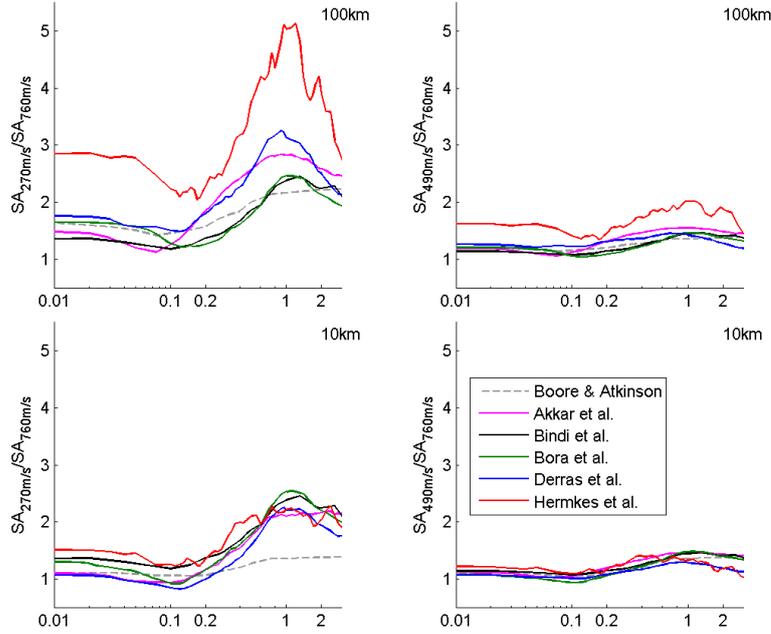
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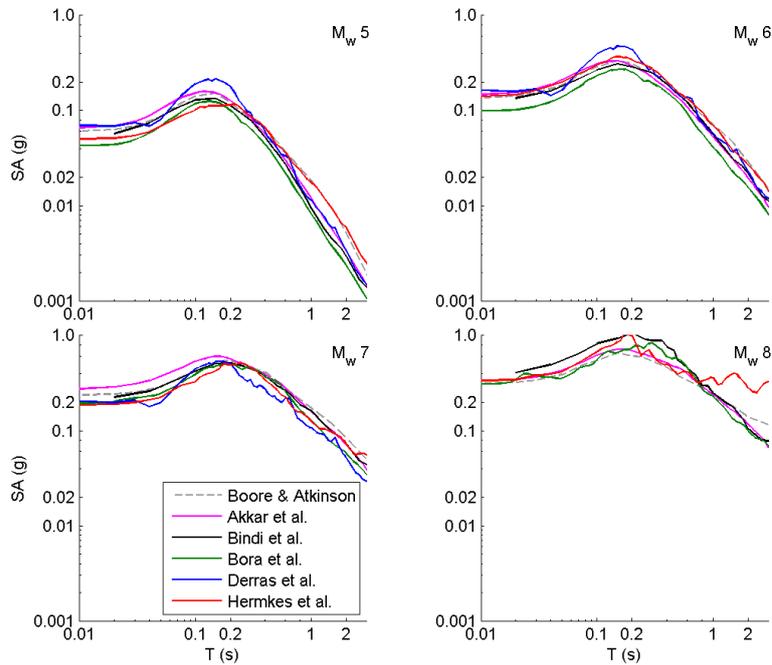


420 *Figure 5 Comparison of  $V_{S30}$  scaling of the median ground motion for  $M_w$  7 strike-slip earthquakes for*  
 421 *PGA (top left), SA(0.2s) (top right), SA(1.0s) (bottom left) and SA(3.0s) (bottom right) at:*  
 422 *a)  $R_{JB} = 100$  km and b)  $R_{JB} = 10$  km.*



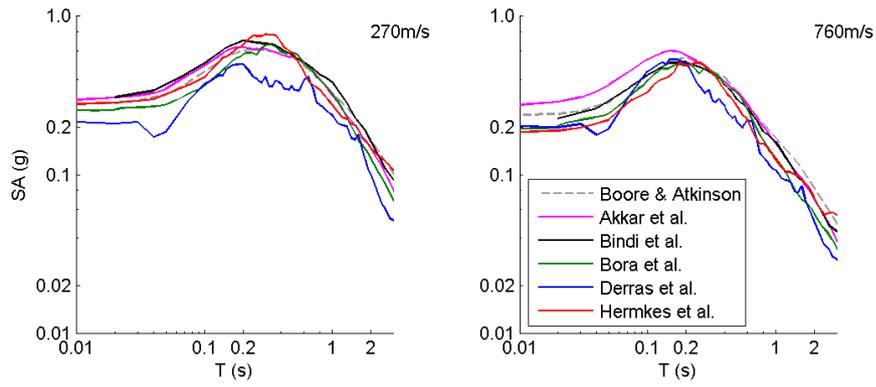
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424 *Figure 6: Comparison of ratios between SA for  $V_{S30}=270\text{m/s}$  (NEHRP D) (left) and SA for*  
 425  *$V_{S30}=490\text{m/s}$  (NEHRP C) (right) to SA for  $V_{S30}=760\text{m/s}$  for  $M_w$  7 (strike-slip) at  $R_{JB}=100\text{km}$  (top) and*  
 426  *$M_w$  7 (strike-slip) at  $R_{JB}=10\text{km}$  (bottom).*



427

428 *Figure 7: Comparison of median 5% damped spectra for strike-slip earthquakes and  $V_{S30}=760\text{ m/s}$*   
 429 *(NEHRP B/C boundary) at  $R_{JB}=10\text{ km}$  for  $M_w$  5 (top left), 6 (top right), 7 (bottom left) and 8 (bottom*  
 430 *right). The predictions from the model of Derras et al. (2013) are not shown for  $M_w$  8 since this is*  
 431 *outside its range of applicability. The other models are shown for this magnitude even though some*  
 432 *developers do not recommend their application for such large events.*



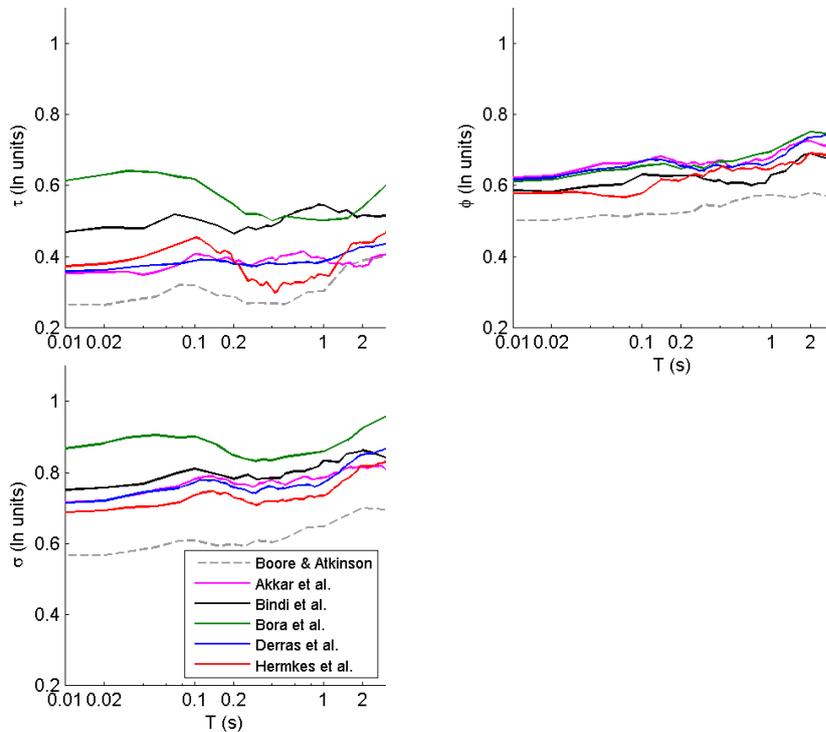
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434

a)

b)

435 Figure 8: Comparison of median 5% damped spectra for strike-slip earthquakes at  $R_{JB}=10$  km for  
 436  $M_w$  7 and a)  $V_{S30}=270$  m/s (NEHRP D) and b)  $V_{S30}=760$  m/s (NEHRP B/C boundary).



437

438 Figure 9: Comparison of the between-event ( $\tau$ ), within-event ( $\phi$ ) and total ( $\sigma$ ) standard  
 439 deviations. All models have homoscedastic standard deviations.

440

441 Table 1: Number of different earthquakes, stations and records used to derive the five models,  
 442 magnitude and distance ranges of the data used, the ranges of applicability recommended by the model  
 443 developers and the exclusion criteria used to select the records used to derive the model.

Model	Akkar et al.	Bindi et al. ( $V_{S30}$ model)	Bora et al.	Derras et al.	Hermkes et al.
Number of earthquakes (E)	221	225	369	320	279
Number of stations (S)	322	345	341	201	251
Number of records (R)	1041	1224	1232	1088	835
R/E	4.7	4.8	3.3	3.4	3.0
$M_{\min}$ to $M_{\max}$ (data used)	4.0 to 7.6	4.0 to 7.6	4.0 to 7.6	3.6 to 7.6	4.0 to 7.6
<b><math>M_{\min}</math> to <math>M_{\max}</math> (recommended)</b>	<b>4.0 to 8.0</b>	<b>4.0 to 7.6</b>	<b>4.0 to 7.6</b>	<b>4.0 to 7.0</b>	<b>4.0 to 7.6</b>
$R_{\min}$ to $R_{\max}$ (km) (data used)	0 to 200	0 to 300	0 to 200	0 to 547km	0 to 200
<b><math>R_{\min}</math> to <math>R_{\max}</math> (km) (recommended)</b>	<b>0 to 200</b>	<b>0 to 300</b>	<b>0 to 200</b>	<b>5 to 200km</b>	<b>0 to 200</b>
Record exclusion criteria (other than in terms of magnitude and distance)	Singly-recorded earthquakes; all three components not available; focal depth greater than 30km; sites with no measured $V_{S30}$ ; structural period beyond usable period range defined by Akkar and Bommer (2006); events with $M_w < 5$ with fewer than 3 records; unknown or oblique style of faulting; not free-field.	Unknown style of faulting; sites with no measured $V_{S30}$ ; singly-recorded earthquakes; only records with low-pass cut-off frequency lower than 20Hz and outside passband of high-pass filter all three components not available; focal depth > 35km.	Not representative of shallow crustal event; unknown style of faulting; only one horizontal component; sites with no measured $V_{S30}$ ; poor quality record; high-pass cut-off frequency higher than Brune-source corner frequency for stress drop of 100bars.	Focal depth more than 25km; sites with no measured $V_{S30}$ ; unknown style of faulting	Unknown style of faulting; sites with no measured $V_{S30}$ ; not free-field conditions; high-pass cut-off frequency higher than 0.25Hz

444